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r&t report

GODDARD SPACE FLIGHT CENTER

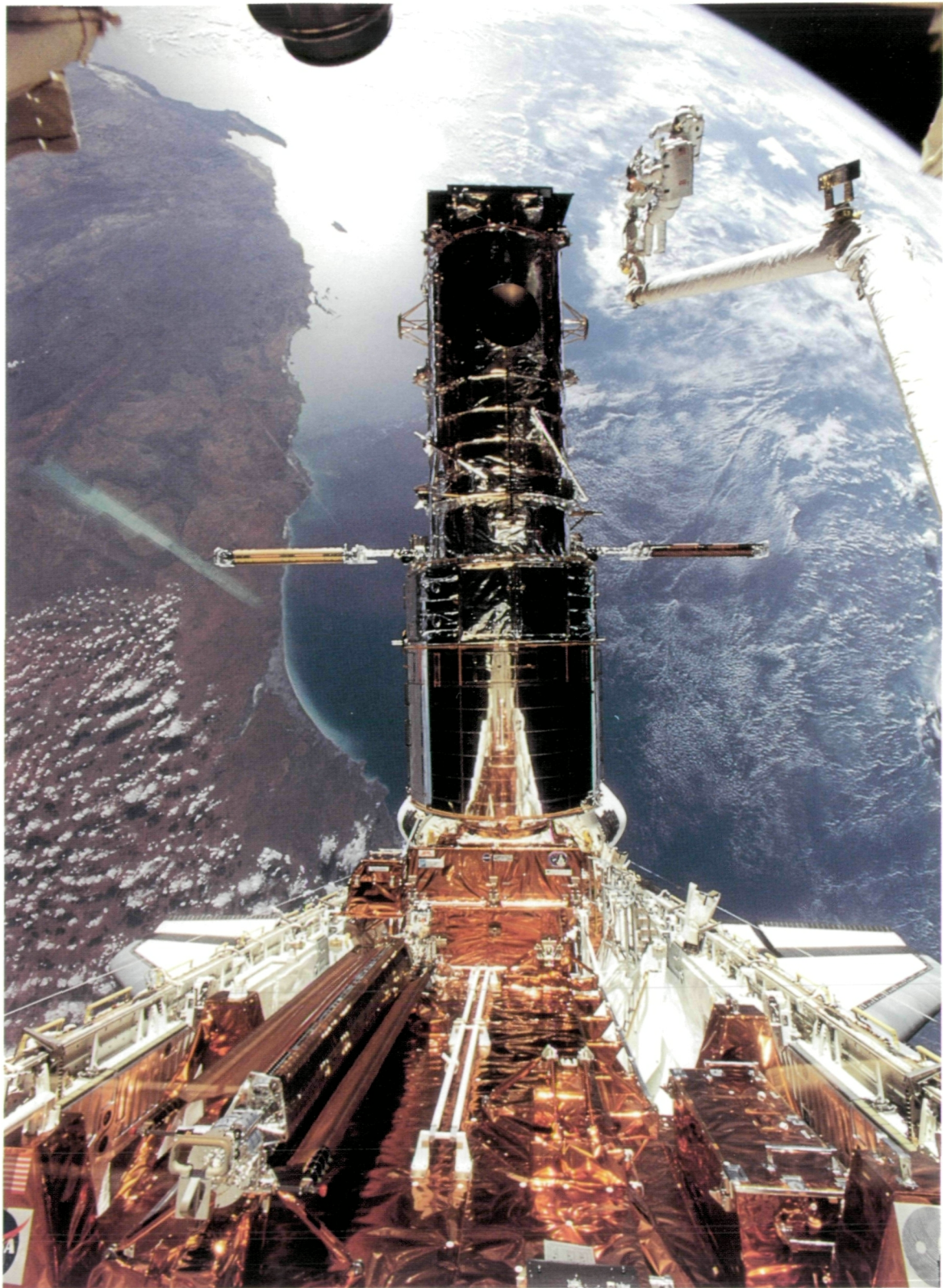
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Research and Technology



This dramatic photo taken from the Space Shuttle Endeavour during the First Hubble Servicing Mission shows the importance of a human presence in space to support Space Sciences missions such as the Hubble Space Telescope. The view of Earth in the background shows the northwestern coast of Australia from the Exmouth Gulf extending up the coastline along the Eighty Mile Beach. The Hamersly Range is the mountain chain on the extreme left of the continent.

RESEARCH AND TECHNOLOGY

R&T REPORT

Goddard Space Flight Center

FOREWORD

This has been a year of remarkable accomplishments for the Goddard Space Flight Center. The success of the First Servicing Mission of Hubble will give us an opportunity to explore the sky with considerably greater resolution than during the first phase of Hubble's existence, which has already gained worldwide attention. The results of the Cosmic Background Explorer continue to fascinate the astrophysical community; the data have stimulated many technical papers, national and international conferences, and inspired contemporary cosmologists to generate new ideas about the origin of our universe. Instruments on the Upper Atmosphere Research Satellite and Meteor (Total Ozone Mapping Spectrometer) have provided important data that have greatly improved our ability to model the chemistry of the Earth's upper atmosphere.

Global socioeconomic changes are reflected in our own national concerns. Redirection of the aerospace industry into new endeavors, the need to modify our educational goals and methods, and the examination of the scale and focus of Federal research is gaining popular attention. In such times of change it is essential that we build on our ability to produce discoveries and developments that help provide direction for our future. While "reinventing government" is a popular phrase that accompanies change, this Center continues on a steady course to follow our vision of exploring the Earth and the Universe.

As exemplified in this year's Report, we continue to develop increasingly more powerful sensors to address the full range of the electromagnetic spectrum. Our optics and cryogenic developments are helping to define state-of-the-art technologies. The use of lasers and lidar in space is coming of age and we are awaiting the results of their widespread use. Data systems, information processing, modeling, and testing the models represent the next cutting edge of science; we intend to maintain our strengths in these important fields. Goddard is developing as a focal point for our entire knowledge base of global change: hydrological, meteorological, geological, and biological.

We are examining new methods of testing new materials, and new ways of handling spacecraft telemetry. System and software engineering have become major players in our planning for the future. Our attention to flight assurance continues to keep us alert for "hidden" dangers. Balloons and sounding rockets again prove to be very useful during this period of capitalizing on small, focused experiments. Our key contribution to the U.S. Global Change Research Program, Mission To Planet Earth, looms large on the horizon.

Our unique relation to a sister agency, the National Oceanic and Atmospheric Administration (NOAA), in developing their observational spacecraft, is an important responsibility that matches our own capability and our interest in the Earth as a planet. Next year's Geostationary Operational Environmental Satellite (GOES) mission will introduce a new line of geostationary spacecraft that will deliver new data to support the need to predict weather and climate changes. In addition, the NOAA-J spacecraft, another Total Ozone Mapping Spectrometer (TOMS) mission, and both the Wind and Polar spacecraft in support of the Global Geospace Science (GGS) mission will be launched.

The vigor and vitality of our technical staff are illustrated by the innovation and new ideas fostered in interdisciplinary fields represented by many of the articles in this report. Science and engineering are the primary strengths of the nation's economy, and I am proud that GSFC continues to retain its place in the front line of so many technical areas.



John M. Klineberg
Director, Goddard Space Flight Center

PREFACE

This year's edition of the GSFC Research and Technology Report is dedicated to the hundreds of people who have contributed to the success of the Hubble Space Telescope First Servicing Mission and to the magnificent window on the universe that they have provided.

Change is the order of the day. One encounters change on every front: global change in terms of the climate; economic change in world markets; political change as exemplified by the collapse of the Soviet Union; change of the millennium a few years away; change in educational methods and school curricula; change in lifestyle; and change in free markets. Should we look at a useful change in the annual Research and Technology Report? We thought so.

This year, we have introduced a format change, hopefully without affecting the book's quality. We are trying a "story board" format. Each article starts on a new page, and wherever possible, we have asked for a single page or a two-page spread to convey the basic idea and the supporting data. The authors are still the people doing the work. We have requested that they try to write to fixed space; in almost all cases, this worked very well. I want to thank these authors for their thoughtful cooperation. We think this format will make the Report easier to read. Certainly the document will be easier to peruse.

One other item of interest we would like to call to your attention is a change in accessibility. The text of this 1993 Research and Technology Report is now being used to describe Goddard research activities in FEDIX,* the on-line database of Federal Government information for colleges, universities, and other interested parties. It, along with a wealth of other information on Federal research and education opportunities, can be accessed via modem at 800-232-4879, or over the Internet at fedix.fie.com.



Gerald A. Soffen
Executive Editor

*FEDIX provides free access to its holdings. Follow the prompts to establish access to the system. To get to the GSFC material, at the first FEDIX menu, choose item (1) Comprehensive Agency Information. At the succeeding menus, choose item (3) NASA, item (5) Space Centers, then item (2) GSFC, respectively. The GSFC menu will present menu items that correspond to the major sections of the R&T Report.

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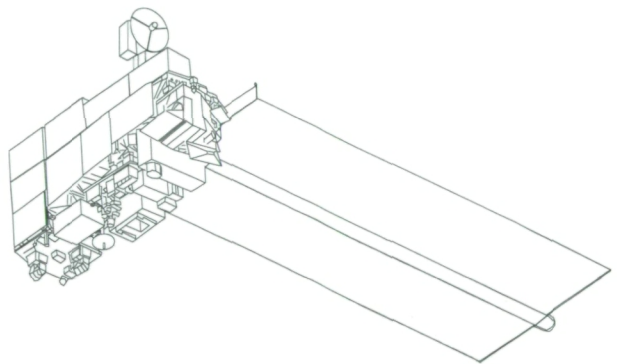
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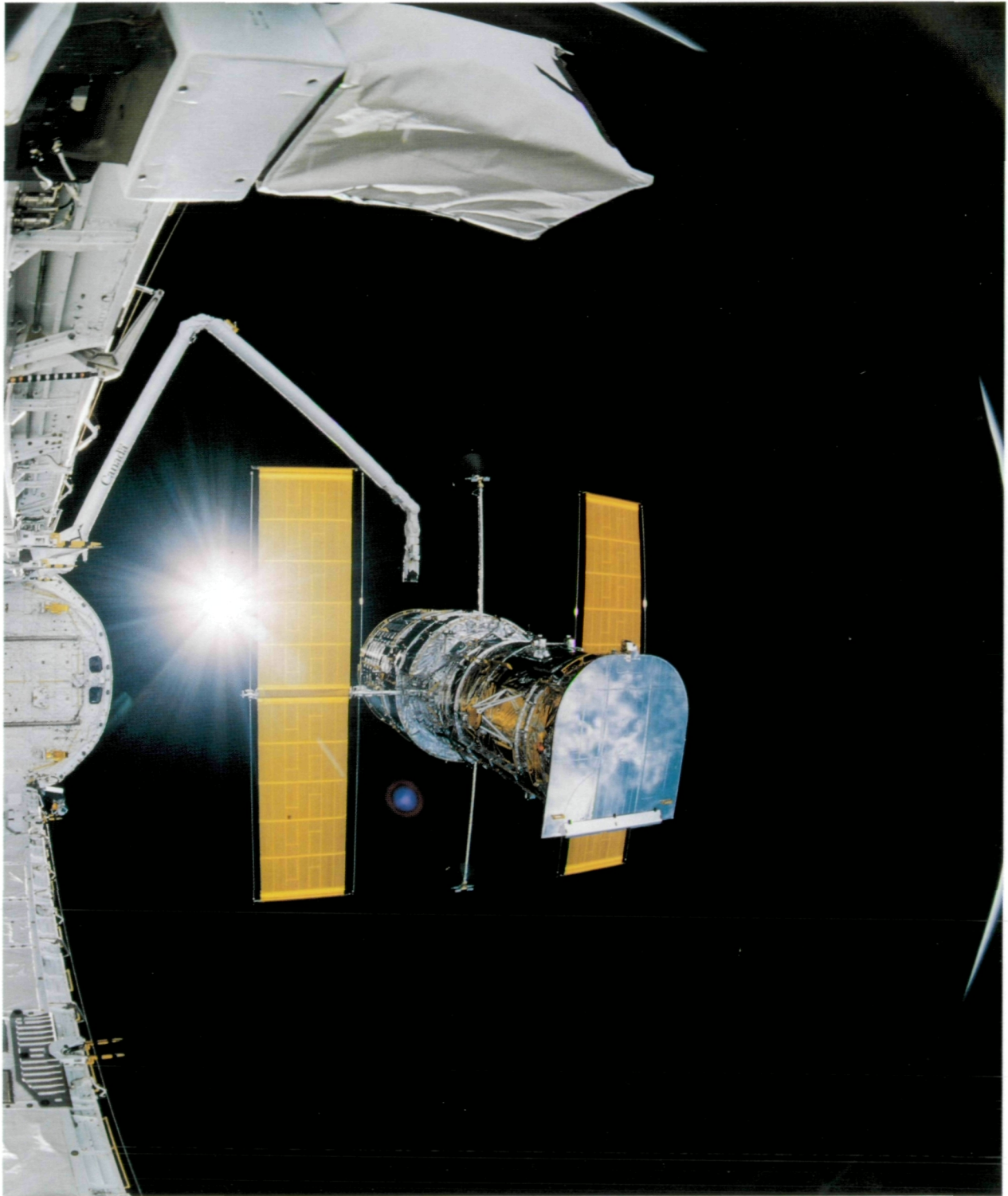
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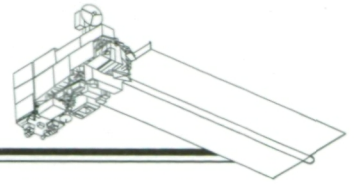
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FLIGHT PROJECTS





Pictured is the Hubble Space Telescope being deployed from STS-31 (Shuttle Discovery) on April 25, 1990. Note the Earth's blue and clouds reflected in the aperture door covering the HST. Seven astronauts are scheduled to repair and upgrade the HST in early December 1993. This Flight Servicing Mission will be the most challenging and difficult manned servicing mission ever attempted.



FLIGHT PROJECTS

AS IS OFTEN the case in the Flight Projects Directorate, this past year has been a truly exciting and challenging one. The activities in 1993 got off to a great start with the very smooth and successful January launch of a Tracking and Data Relay Satellite (TDRS F-6) on the Shuttle with an inertial upper stage. The Directorate managed U.S. participation in the Spectroscopic X-ray Observatory (ASTRO-D) mission, which was built and launched in February by our Japanese partners. A GSFC-managed weather satellite, NOAA-I, was also successfully launched on a GSFC-managed Atlas launch vehicle from Vandenburg Air Force Base. Other Flight Projects Directorate launches included the Air Force Radar Calibration (RADCAL) satellite on a Scout launcher and secondary payloads, Small Expendable Deployer System (SEDS) and Plasma Motor Generator (PMG) on Air Force-managed Delta vehicles. With the exception of NOAA-I, which failed suddenly several weeks after a flawless launch and on-orbit checkout, all of these missions have been totally successful.

Other Flight Projects Directorate missions made excellent progress through the year towards planned 1994 launches. These include the Geostationary Observational Environmental Satellites (GOES) weather satellite, the Total Ozone Mapping Spectrometer (TOMS), Wind and Polar, which are key components of the International Solar Terrestrial Physics program, and NOAA-J, which will replace NOAA-I.

Three Directorate projects (EOS-AM, EOS-PM, and the Chemistry and Special Flights Projects) are part of the ambitious Earth Observing System program. Together, these missions comprise the data-gathering, or flight portion of EOS, which has as its objective the measurement, distribution, and analysis—over a 15-year period—of those geophysical parameters which govern the processes of global climate change. With launches beginning in 1998, these missions are in early, but very active, phases of development. The Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) Project initiated an in-house Phase B study and selected instruments to be developed; the Explorers Project office managed

development of the X-ray Timing Explorer (XTE) spacecraft and definition of the Advanced Composition Explorer (ACE) and the Far Ultraviolet Spectroscopic Explorer (FUSE) missions; and the International Projects office continued to lead GSFC participation in a number of international missions.

In intensity and urgency, none of these missions exceeded the levels achieved by the Hubble Space Telescope (HST) project. The initial excitement and anticipation generated by the launch of HST in 1990 was soon dampened by discovery of the now-well-known spherical aberration flaw in the primary mirror. Despite a large volume of very significant scientific discoveries, HST's full potential cannot be achieved in its present state. As of the time of this writing, the HST First Servicing Mission (FSM) is less than 3 months away. As highlighted by the cover photo, and explained in detail in a number of feature articles in this publication, the FSM will be the most challenging and difficult manned servicing mission ever attempted. Its goal is to restore HST to very nearly its original capabilities. If not fully successful, it will not be for lack of effort.

A large and highly skilled team of NASA and contractor personnel has been preparing diligently over the past several years for this unprecedented challenge. Extensive in scope, and meticulous in detail, the preparations have progressed remarkably well this year. The new instruments have been built, tested, and delivered to the launch site. Every critical measurement has been checked, rechecked, and independently verified. All of the replacement components are mounted in their carriers and ready to go. Over 150 special tools have been designed, built, and tested—in cleanrooms, underwater in the Neutral Buoyancy Simulator, in manned thermal vacuum tests by the astronaut team, and, in some cases, in space. The extensive schedule of simulations is underway and contingency plans have been developed, practiced, and tested. The software has been verified, both line-by-line and at the system level. Many minds have been challenged and pressed to the limit. All that remains is to do it!

Vernon J. Weyers

HST SUCCESSFULLY SERVICED AND RE-DEPLOYED

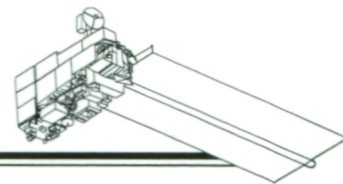
History will record the First Hubble Servicing Mission as one of the most significant achievements in the History of NASA. The STS-61 mission illustrated the successful application of all NASA resources combining to restore the image of Hubble, NASA's can-do reputation, and the interest of the world in space exploration. The significance of this mission and Hubble goes far beyond what we can imagine today. Analysis from the much-improved Observatory will solve many mysteries of the Universe and raise new questions for future generations to answer.

Here at Goddard, not only the Hubble Team but the entire Center played a significant role in this mission. Everyone at Goddard, and the entire HST Project Team, should be proud of what was accomplished. Additionally, team personnel from KSC, JSC, and NASA Headquarters played major roles in overall mission success.

The technical leadership and planning for the HST first Servicing Mission included the development of all scientific instruments and spacecraft hardware for use during this mission, as well as the next three planned servicing missions. The design, development, and construction of the many carriers, tools and instruments used during HST servicing activities were flawless. Systems development, testing, verification and application were performed well within timeline requirements. Without the tireless efforts of all team members, including on-time delivery of all flight support tools and equipment, development of required flight software and database updates, and the preparation of operating procedures and contingency documentation, the STS-61 Hubble Servicing Mission would not have been possible.

The activities accomplished by the crew were real demonstrations of skill and dedication to mission success, restoring the Hubble and NASA's image, and represented some of the most significant activities performed in space to date. The primary objective of the mission, the improved optical performance of Hubble, remains to be demonstrated. In February 1994, we will see the restored imagery that will complete this success story.

*Joseph H. Rothenberg
Associate Director
of Flight Projects for
Hubble Space Telescope
12/17/93*



A SPACE INVESTMENT STRATEGY PUT TO THE TEST

IN DECEMBER 1993, seven astronauts flew a Space Shuttle to the Hubble Space Telescope and conducted the most challenging set of space repairs and upgrades ever attempted. The stakes are high, both for astronomy and for the future of the exploration of space. Yet perhaps the most important idea being put to the test is not one of engineering or science, but is rather a strategy of economics and investment.

Investment in exploration has always been a rather risky business. Exploration must implicitly involve the unknown, and yet sound investments are based on making the right calculation of risk and return. A particular difficulty of ventures into uncharted waters is that prospects for return tend to be in the long term. Of course, early difficulties are common, and can be interpreted either as part of the inevitable learning process or as harbingers of doom. NASA decision-makers must make choices in the face of this risk and uncertainty just as have explorers in the past, or as venture capitalists today.

The Hubble Space Telescope has earned early notoriety for the flaw in its primary mirror, but more importantly, it is the first test of a strategy to achieve high productivity over the life cycle of a space mission using on-orbit servicing by the Space Shuttle. The Hubble strategy required a heavy investment into initial capability (the space science equivalent of plant and equipment), both to provide the unprecedented performance levels of this spacecraft, and to provide the capability to produce an exceptionally high volume of quality scientific data for a long operational lifetime. The validity of this economic strategy of the Hubble program has been debated endlessly in the 15 years since it was begun, but only now can the first results be judged. Hubble's size and budget were much higher than many other robotic NASA missions, but so were Hubble's intended capabilities to observe targets and take data. Although a large up-front investment was required to develop the capability for servicing, this investment was expected to pay off from the ability to substantially upgrade capabilities at a small fraction of the cost of a new observatory, and by the extension of mission life to 15 years.

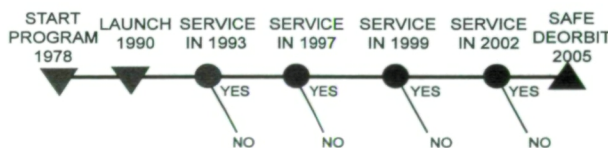
It was also considered essential to protect this large investment by providing the ability to recover from the potential for spacecraft failures which have been historically experienced. Two of four of the Orbiting Astronomical Observatories failed in the 1960s and 1970s—a

major blow to a program which cost several billion in today's dollars. In the 1960s and 1970s, the failure rate of NASA spacecraft was 10 to 20 percent. Even in the 1980s and so far in the 1990s, the failure rate experienced by commercial, civil and military spacecraft worldwide has remained at about 15 percent. The potential to use Space Shuttle servicing to recover from absolutely unforeseen difficulties is especially important in light of HST's mirror flaw.

In reviewing this strategy in retrospect, it is clear that the up-front costs were substantially higher than expected, and the capabilities of the Space Shuttle did not develop to the expected level of 40 flights per year. However, the critical question should not be, "Did everything go according to plan?" but rather, "Given the current situation, what are the potential options for future investment, and how does the return on these potential investments compare with the usual alternatives?"

To compare the Hubble strategy with other alternatives, one must account for the fact that the investment choices posed by the Hubble program are different from those usually seen in space science. In NASA's first 35 years, the normal way of doing business has been to launch a science spacecraft, reap data for as long as it functions, and then end the mission. Where a long-term science program was desirable, a series of spacecraft was built and launched. The Hubble strategy is unusual in that it provides five 3-year missions, all using the same spacecraft in orbit. Conceptually, the Hubble program can be viewed as a series of investment decisions.

Hubble is approaching the end of the first 3-year phase of operational lifetime. NASA has also already spent a major portion of the investment in the first Shuttle servicing mission to correct the mirror flaw, and in the upcoming 3 years of operational lifetime that it will yield. Initial technology investments have been made to support the subsequent 3 years of lifetime, which will be provided through a second Shuttle servicing mission in



Investment Decision Tree.

FLIGHT PROJECTS

March 1997, and to provide Hubble with unprecedented capabilities for ultraviolet spectroscopy and near-infrared astronomy. The process of upgrade and life extension continues through the fourth mission in 2002, with a fifth and final servicing mission to return the 25,000-lb spacecraft safely to Earth. While these upgrade missions must invest in state-of-the-art technology to upgrade the quality of the scientific instruments inside Hubble, NASA avoids the costs of an entire observatory and the risks of launch failure and infant mortality.

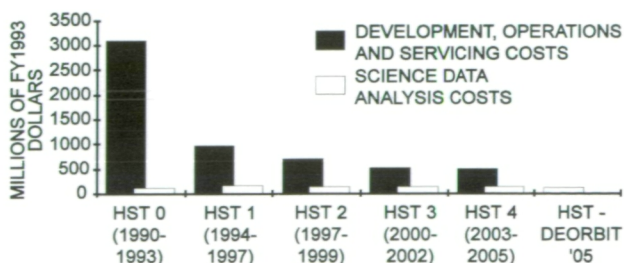
How do the costs and benefits tradeoff? If costs are attributed to each phase of the Hubble mission, it takes half of the entire life-cycle budget just to build the observatory to the required specifications and operate it until the first servicing mission—the phase of lifetime referred to as HST 0 in the chart below. To develop and prove the servicing concept, which will result in the restored HST performance from 1994 through 1996, will take another one-sixth of the life-cycle budget. The remaining three phases (9 years) of HST life will essentially require the remaining one-third of the HST budget, with a small cost at the end to return HST to Earth.

The Hubble Program is designed to achieve its maximum scientific productivity during the last three operational phases. The true output of the Hubble Space Telescope Program is high-quality data in the hands of scientists exploring the Universe. A measure of the cost effectiveness of a space science program is how much “other effort” is required to produce this fundamental product. In the last three phases of the HST mission, 20 cents of every dollar will go to scientists to analyze data that Hubble is capturing, a cost-effectiveness ratio more than twice as high as historically experienced with the vast majority of science spacecraft. If Hubble is operated for 15 years, the lifetime cost effectiveness will be over 10 cents of return per dollar invested, about 25 percent above average. In contrast, if Hubble is terminated after 1996, the ratio of data analysis to other costs will only be about six cents on the dollar. The last three periods are intended to contribute

substantially to life-cycle productivity by reaping the return from using an already-built and tested spacecraft system. Given the scale of the HST Program, this means that Hubble can produce a very high volume of cost-effective scientific research.

But high-volume cost effectiveness is not enough. The quality of the data that are produced must also be competitive with alternative investment options. All science spacecraft that survive a long time tend to have a high ratio of data analysis to up-front and operational costs. One area in which Hubble differs from those spacecraft is that state-of-the-art instrument technologies will continually update Hubble capabilities, so that the level of quality will increase over time. The instrument technology currently inside Hubble is essentially from the late 1970s. The First Servicing Mission is primarily concerned with correcting for the mirror flaw, and thus new technology enhancements are limited. Only with the second servicing mission will the full plan of technology enhancements be seen; orders-of-magnitude improvements are a fairly safe prediction for subsequent upgrades based on technology performance already demonstrated in the laboratory on Earth.

The strategy of the Hubble Space Telescope is an adaptation to space science of the paradigm of economies of scale and high-volume production that propelled American industry forward in the 20th century. For American business today, facing the challenge of low-wage international competition, the high-volume production paradigm is becoming obsolete. However, the current use of space for scientific exploration is drastically different from the state of industrial competition on Earth. The question in space is not whether high-volume production is becoming obsolete, but rather are the space-faring capabilities in the 1990s sufficiently mature to support this next step? Can NASA productively sustain a permanent facility in space? Can the benefits of high-volume scientific data production in space be realized? These are the fundamental questions to be answered by the first Hubble servicing mission.

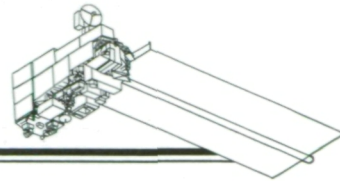


Life-Cycle Costs.

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TECHNOLOGY BENEFITS ARISING FROM HUBBLE SPACE TELESCOPE'S FIRST SERVICING MISSION

THE BOLD PLAN to remove the spherical aberration from each light path within the Hubble Space Telescope (HST) instruments includes building to meet optical fabrication and alignment tolerances that significantly exceed the requirements for HST as originally designed, or, for that matter, for any other spacecraft. To meet these requirements, novel methods have been employed which have pushed existing technology. We can only begin to understand the benefits and long-term implications of this effort at this time.

Correction of the spherical aberration of the light collected by the 2.4-meter (m)-diameter primary mirror is done with nine small mirrors less than 1 inch (12 to 25 mm) diameter. These mirrors are on each of the five optical paths of the new Corrective Optics Space Telescope Axial Replacement (COSTAR) Deployable Optical Bench (DOB) and within the optical paths to each of the four detectors of the replacement Wide-Field/Planetary Camera (WF/PC). The corrective mirror elements on each of these nine optical paths can be visualized by thinking of each as being positioned at a point where the surface of the primary mirror is re-imaged. Each mirror replicates the inverse of the wavefront error introduced by the primary, as seen at their respective locations (the mirrors are not identical because of differences including the on- and off-axis locations of the incoming light). Producing these mirrors, especially the off-axis anamorphic aspheres for COSTAR, and testing them was a challenge to potential fabricators. The specifications for COSTAR mirrors included one-hundredth wave rms surface figure (one-hundredth of the wavelength of HeNe laser light) and 1.0-nm rms surface roughness. The potential high costs to produce them by existing conventional technology mirrored the challenge.

Computer-generated holograms (CGHs) could be used in early optical testing and for final, precise testing with a combination of physical lenses and analyses that would null errors in software. This concept of using a "software null lens" and the generation of the CGHs with software were understood in principle before HST funded this work. However, the funding to resolve residual errors in the software and to bring this technique on-line had been inadequate before the First Servicing Mission (FSM) opted to use CGHs to meet requirements for performance and redundant test methods. Having successfully applied this technology to the production of the COSTAR mirrors will

allow the same technology to be applied to mirrors used in microlithographic processes in the production of computer chips. The use of more precisely figured aspheric mirrors has potential for moving from visible light to the use of ultraviolet and even x-ray wavelengths in the production of smaller or more densely packed computer chips. This, in turn, has implications throughout industries using computer technology—from more powerful and faster supercomputers to more affordable low-end computers and other products using increasingly powerful mass-produced microchips.

Requirements for redundant tests also resulted in the development of an instrument to measure wavefronts of the telescope simulators used in the program (see the article on the "Aberrated Beam Analyzer," in this report).

Other technologies have advanced under the FSM and, while their implications may be less clear, they do point to other benefits that will likely come from the work done under this program. For example:

- To meet the more stringent alignment requirements for WF/PC-II to position the image of the primary mirror onto the surface of each corrective element (to within 1 percent of its diameter), it was decided to implement on-orbit alignment capability: electrostrictive actuators were incorporated behind folding mirrors for three of the four WF/PC detectors to make the minute corrections that could be necessary after launch. This technology uses a material that changes its length in response to an applied voltage. This dimensional change is used to tilt the mirrors with tiny actuators in a restricted space. This technology was previously used in adaptive optics applications; its successful application in WF/PC-II opens up the possibility for similar applications.
- A concern over particulates and other contamination of the COSTAR mirrors led to intensive review and development of a cleaning process using carbon dioxide "snow." The process can remove contaminants left after cleaning with gases due to boundary layer effects that inhibit the interaction of gases with very small particles on the surfaces. The "snow" technique also can be performed without damaging surface coatings (particularly magnesium fluoride) on sensitive

space optics, as has been seen with the use of wipes or chemical washes. As it turns out, this technique was not actually used on COSTAR because of the margins that were achieved in throughput due to the superior reflectivity of the coatings. However, this technique holds promise for future programs including ground-based telescopes or any other highly sensitive optics because of the greater confidence in its use.

- In order to make on-orbit correction to images required because of the spherical aberration in the HST primary mirror, researchers had to characterize the error while HST was in orbit, and convince themselves (and others scrutinizing the proposed repair scenario) that they knew where the error lay. In part, this was done by examining the so-called "fossil data" from tests that had been performed on the ground and by evaluating intact test equipment. The technique of "phase retrieval" was employed to independently arrive at a value for the conic constant, which characterizes the aberration. Developing this technique for analyzing the performance, alignment, and defining parameters of an optical system by examining the images it produces has resulted in the publication of considerable technical material. Phase retrieval was also used to find the best focus during a test at GSFC in which an unaberrated source was provided as input to the COSTAR, and detected with a European Space Agency-supplied ground-based replica of HST's Faint Object Camera.
- The requirements of the FSM for the precise spherical aberration-correcting mirrors and redundant testing also drove development of noncontact profilometry. This technology measures surface curvature with two parallel laser beams to derive local surface curvature. This is a powerful technique to analyze the surfaces of high-quality mirrors, includ-

ing exotic aspherical designs. The state of the art was advanced with the FSM-funded delivery of the first such profilometer, which incorporates circumferential scan capability.

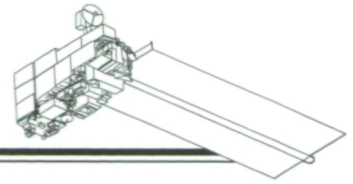
- Finally, HST's unprecedented astronomical imaging results and discoveries, despite the well-known flaw and bad publicity, owe much to the image enhancement techniques that have been employed. Computer techniques used in such fields as space-based ground imaging, radio astronomy, and medical technology (such as positron-emission tomography), have been translated into new algorithms that were applied to HST's images. This transfer of information and cross-fertilization of fields benefits all who use the technology.

The drive to meet the novel requirements of the HST FSM and the requirement to implement redundant test methods has advanced technology in several areas related to optical systems. The benefits range from the productive interchange of ideas and techniques for image enhancement and the use of electrostrictive devices, to the advancement of optical technology through the use of a "software null lens" and computer-generated holograms to produce exotic aspherical optical elements.

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HST BENEFITS: ADVANCES IN DETECTOR TECHNOLOGY

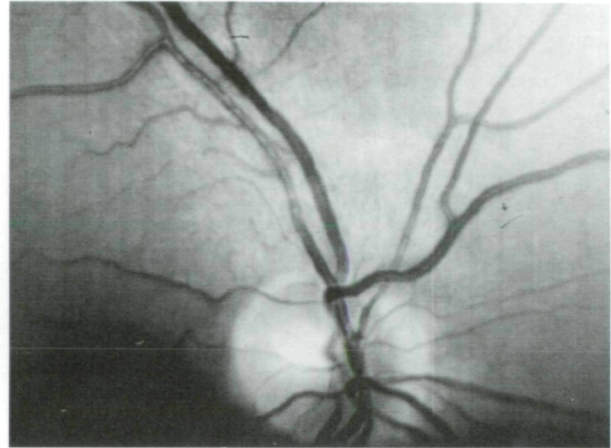
THE "EYES" of the HST scientific instruments—their detectors—have become the "eyes" for a number of innovative applications on Earth. Advanced requirements for HST instruments have provided impetus for technology performance gains and the utilization of similar technology in several existing and new products.

The "eyes" of the WF/PC-I, which is currently returning state-of-the-art science from HST, and WF/PC-II, manifested for launch on the FSM in 1993, are charge-coupled device (CCD) cameras that use devices fabricated by Texas Instruments and Loral, respectively. Both instruments were designed and built by the Jet Propulsion Laboratory (JPL). In both cases, HST instrument performance requirements drove investments in design and process improvements that have contributed to expanding the performance margins of the CCD industry.

The basic operation of a CCD involves four steps. First, incoming photons generate free electrons in the device via the photoelectric effect. The photoelectrons are then collected at discrete sites on the device, called pixels, defined by an array of electrodes, or gates. The voltage on the gates is manipulated to move the collected packets of photoelectrons from one pixel to the next down the vertical registers of the device, like a bucket brigade. At the end of each vertical register, a horizontal register collects one line at a time and transports the packets serially to an amplifier. Finally, the individual charge packets are converted to a voltage, which can be displayed on a monitor to recreate the original image.

CCDs are found in many commercial products, such as video cameras. The large-format, low-noise, high-charge-transfer efficiency requirements of the WF/PC instruments have contributed not only to better performance for a wide range of commercial applications, but also have driven improvements in substrate and process technologies that can result in better yield and, thus, lower cost.

Medical imaging is an area where CCDs are finding an expanding market, and actual WF/PC CCDs are part of this expansion. CCDs can replace x-ray film in many applications, allowing real-time evaluation, and dramatically reducing patient exposure time to x-radiation. Soft tissue scans, such as mammograms, and dental procedures, such as root canals, can be performed more efficiently, since time need not be taken to develop in-process images, and evaluation may be quickly performed. The figure shows



An image of an optic nerve, taken with a room-temperature WF/PC-II CCD that replaced film at the camera focal plane.

an image of an optic nerve, taken with a room-temperature WF/PC-II CCD that replaced film at the camera focal plane. These CCDs are currently being evaluated by ophthalmologists in the field.

CCD technology developed for WF/PC is also supporting a variety of advanced instrumentation applications, from x-ray imaging spectrometers to scanning electron microscopes and imaging particle detectors. The Space Telescope Imaging Spectrograph (STIS), being developed by the GSFC Laboratory for Astronomy and Solar Physics (LASP) and scheduled for launch in 1997, has established as a baseline design large-format (1 million pixel) CCDs that are illuminated from the back to enhance ultraviolet sensitivity by avoiding the absorption of radiation by the gates on the front. The techniques developed by SITE (formerly Tektronix CCD Products) to meet the high-performance, low-noise, low-dark-current requirements for STIS are applicable to performance and yield improvements across their large-format commercial product line.

The infrared "eyes" of the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), being developed by the University of Arizona for installation on HST in 1997, are three mercury cadmium telluride (HgCdTe) focal plane arrays. These infrared arrays, produced by Rockwell International Corporation's Electro-Optical Center in Anaheim, California, are each composed of over

FLIGHT PROJECTS

65,000 individual elements, or pixels, each of which is a transducer that converts faint infrared signals into electrical outputs. The time-shared information generated by the array is fed to a display or computer, where a complete image is formed in much the same way that the human brain creates an image from the electrical signals fed to it from the focal plane in the human eye. The high resolution and sensitivity required by the NICMOS instrument have already been demonstrated in photographs taken through ground-based telescopes worldwide. The NICMOS-type focal plane arrays will give HST the ability to conduct planetary, stellar, and galactic observations in the short-wavelength infrared region that were not previously possible. Scientists generally agree that these arrays have revolutionized infrared astronomy.

The improvements in high-resolution infrared detector technology fostered by the NICMOS program have resulted in the development of several commercial applications. The NICMOS focal plane arrays are being developed for use in systems to facilitate drivers' night vision and night/obscure weather aircraft landing, airport

and industrial security, Earth surveillance, and medical thermography.

Advances in HST detector technology have provided a driving force for the detector industry to move the boundary that defines state-of-the-art capability in process techniques and device performance. These benefits for existing and new products extend far beyond the HST.

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Sponsor: Office of Space Science

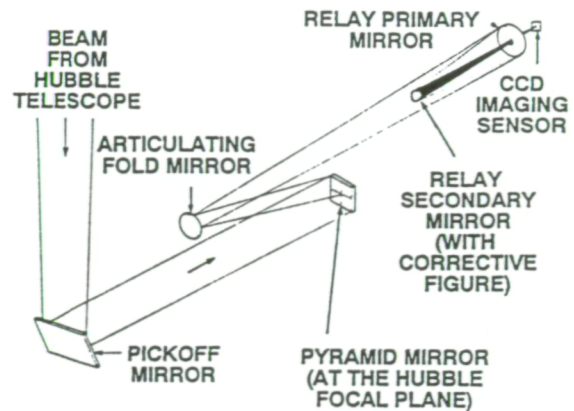
Ms. Carolyn Krebs is Scientific Instrument Manager for the HST Space Telescope Imaging Spectrograph (STIS) and also serves as detector development interface for all HST instruments. Prior to joining NASA in 1991, she was Branch Chief (Microphotronics) at McDonnell-Douglas Electronics Systems Company, responsible for laser diode research, development, and production, and was Program Manager of diode-pumped slab laser development for space-based applications.

of -1.0023, the primary mirror conic constant was closer to -1.0139. While the conic constant error greatly degraded the imaging capability of WF/PC-I, this error proved to be fortuitous for WF/PC-II, in that the fix, in principle, would be relatively straightforward. By the time the aberration was discovered, many of the optical components for WF/PC-II were already through fabrication. To recover from the defect in HST, the requirements for the WF/PC-II optical system were modified to correct the spherical aberration to the fullest extent possible. This resulted in several changes to both the optical components and the alignment tolerances.

To understand how the correction was implemented in WF/PC-II, a short tutorial on the optical system is needed. For each camera in WF/PC, there is a two-mirror relay element, or Cassegrain telescope, consisting of a primary mirror and a secondary mirror, that serves to re-image the pupil from the HST primary mirror onto or near the secondary mirror in the relay. The second figure shows the layout of the WF/PC-II optical train for one camera. In the case of the WF relays, the image on the HST primary is re-imaged directly onto the relay secondary. For the PC, the HST primary image is re-imaged close to the relay secondary, but not precisely on the secondary. Since the defect in HST was on the primary mirror and the image from the HST primary was re-imaged on the relay secondary, the defect in the HST theoretically could be corrected by placing an equal—but opposite—defect on the relay secondaries.

This was the approach taken on WF/PC-II to correct the wavefront from HST's flawed primary mirror. The shape of the relay secondary mirrors, each about the size of a nickel, was changed to include an aberration equal and opposite to that in the HST. In effect, the error in HST was cancelled by an equal and opposite "error" placed on the WF/PC-II secondary mirrors. For the planetary camera optics, the small, previously flat "fold" mirror also had to be polished slightly convex so the image from the HST primary mirror would be focused exactly onto the relay secondary.

In principle, these modifications to the optics were relatively straightforward; however, not only did the image from the HST primary have to be focused on the relay secondary, but it also had to be precisely centered. Several studies were performed and an optical error budget was developed which showed that the pupil alignment or centering had to be within 1 percent of the diameter of the relay secondary (1-percent pupil shear). If the alignment was not maintained to within 1-percent pupil shear, another defect—coma—would be introduced, quickly de-



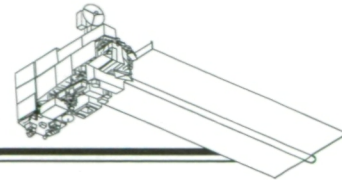
The layout of the WF/PC-II optical train for one camera.

feating the aberration correction and making WF/PC-II no better than WF/PC-I.

During the spring and summer of 1991, a significant amount of effort was expended to determine the alignment stability of the instrument. The primary concern was whether the 1-percent pupil shear requirement could be initially met, and then maintained both during launch and for operation on-orbit through end-of-life. Tests and analyses were conducted with the flight hardware, and the on-orbit data from WF/PC-I were also analyzed. There was evidence that the alignment of WF/PC-I was slightly different from the alignment that had been observed prior to launch. This was not a problem for WF/PC-I, but in the case of WF/PC-II, with its high sensitivity to pupil centration, it could have a significant effect.

The most straightforward means of adjusting the position of the pupil was by controlling the tip and tilt of the pickoff mirror and the fold mirror on each optical train. In this manner, the pupil could be precisely centered on the relay secondary and could be updated or adjusted from the ground as required throughout the life of the instrument. In addition, by having active tip and tilt control, the initial requirements for ground alignment could be slightly relaxed.

To assure that the alignment could be attained and to alleviate concerns about long-term stability, alignment control that could be actively commanded from the ground was incorporated into the design of WF/PC-II. To compensate for the added cost associated with these changes, the instrument was descoped to eliminate four of the original eight cameras. The final configuration of WF/PC-II contained three WF cameras covering an L-shaped field



of view 2.63 by 2.63 arc minutes on a side, and a single PC camera with a square field of view covering 34.2 by 34.2 arcsec. Three of the fixed-fold mirrors were replaced with Articulating-fold Mirrors (AFMs), and the alignment of the remaining camera and associated optical train was controlled by a two-axis tip/tilt mechanism that was added to the pickoff mirror. It was believed that the highly complex pyramid mechanism, which was used on WF/PC-I to switch between the WF mode and PC mode, was the cause of the alignment variations observed on-orbit with WF/PC-I. This mechanism rotated the pyramid mirror 45° to switch between the two modes and also provided a small amount of focus adjustment. With the WF/PC-II descope to only four cameras, the placement of the cameras could be configured such that the switching was no longer needed. The focus capability was also not needed, especially since, in the case of WF/PC-II, axial movement of the pyramid mirror caused pupil misalignment which, in turn, introduced coma. Focus could be adjusted by moving the HST secondary mirror and adjusting the focus of the COSTAR as needed. As a result, the pyramid mechanism was ultimately replaced with a hard-mounted, fixed-pyramid mirror.

The decision to develop the AFMs was made less than 2 years prior to the required delivery of the instrument, and only 10 months prior to when they were needed for integration into the optical bench. Due to the tight schedule, a "skunkworks" mode was adopted for the design, development, and test of the AFMs.

Since most of the WF/PC-II hardware was in the final stages of fabrication when the AFM decision was made, the most significant engineering challenge was packaging the AFMs to fit within the volume occupied by the existing fixed-fold mirrors. The front surface of the mirror could not be moved forward without affecting the optical design of the instrument, while the back of the envelope could not be expanded because of an existing filter wheel assembly.

The packaging constraints made a conventional motor and gear train (such as that used on the pickoff mirror mechanism) impractical. Three solid-state actuators—magnetostrictive, piezoelectric, and electrostrictive—were considered, and two ruled out because of their hysteresis and tendency to drift. The electrostrictive approach was selected because it offered the required precision and could be packaged within the available envelope. The entire AFM assembly, including the mirror, was approximately 1.5 in diameter by 0.75 in deep, and could correct for up to plus or minus 5-percent pupil shear with a 1-arcsecond step size.

With this configuration, the Pickoff Mirror Mechanism (POMM) would be used to align the one WF channel that still had a fixed-fold mirror, and the AFMs would be used to align the remaining two WF channels and the PC channel. Using this approach, the optical alignment, which is critical to correct the HST error, could be guaranteed with sufficient margin to manage any unexpected conditions or long-term drift.

Integration of WF/PC-II was completed in January 1993, and system-level testing at JPL was completed in May 1993. The system-level test culminated with a successful 32-day thermal vacuum test that demonstrated the performance of the instrument. The optical performance was better than originally anticipated, and from a contamination point of view, the instrument was cleaner than expected.

The instrument was delivered to GSFC on June 4, 1993, fully 2 weeks ahead of schedule. Throughout the summer, a series of tests was conducted which were intended to demonstrate mechanical and electrical compatibility between WF/PC-II and the hardware it will interface with during the mission, specifically the Scientific Instrument Protective Enclosure (SIPE), HST, and the various tools and crew aids that will be used during the EVAs. The testing was accomplished by integrating WF/PC-II with the Vehicle Electrical System Test (VEST), the SIPE, the High Fidelity Mechanical Simulator, and the flight EVA tools and the crew aids. All of the testing was successfully completed, and the instrument was shipped to Kennedy Space Center (KSC) on August 18, 1993.

At the present time, WF/PC-II is undergoing final checkouts at KSC in preparation for integration into the SIPE. Once installed in the SIPE, the instrument will not be touched or seen again until the astronauts open the SIPE door and install WF/PC-II into HST. The results of the thermal vacuum test suggest great performance for WF/PC-II, and if that expectation is fulfilled, we should have images early next year that demonstrate the full capability of the HST.

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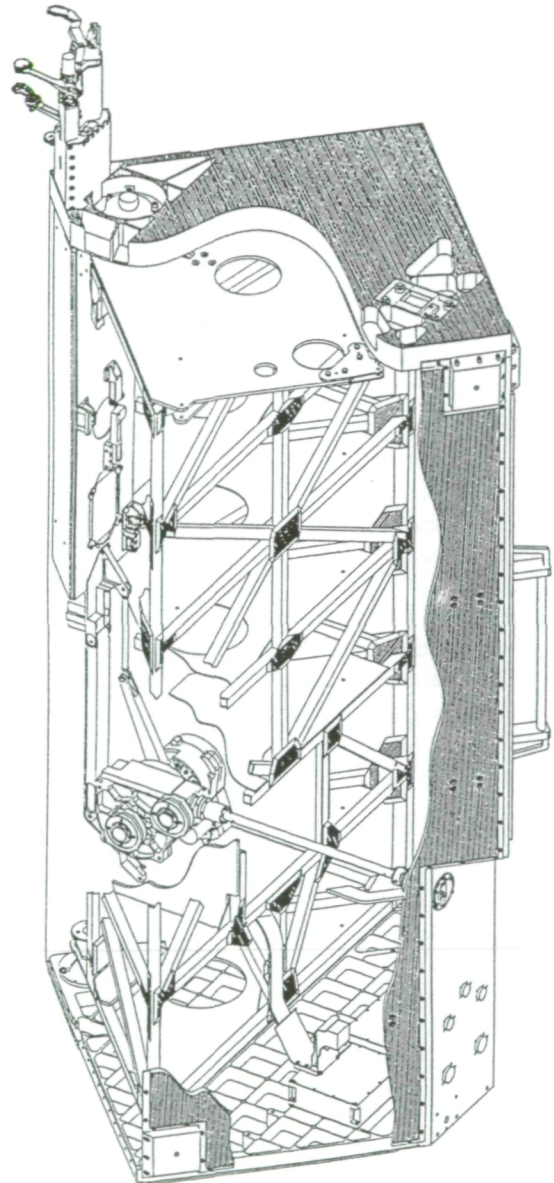
THE DEVELOPMENT OF THE CORRECTIVE OPTICS SPACE TELESCOPE AXIAL REPLACEMENT

SPHERICAL ABERRATION caused by an incorrect figure in the HST primary mirror has significantly affected the HST's performance. COSTAR—a key element in the First Servicing Mission for HST—is an instrument designed to correct spherical aberration for HST's first-generation axial scientific instruments. It will help restore HST's potential to allow scientists to study faint, distant, and closely spaced objects in the cosmos. COSTAR was built for the HST Project by Ball Aerospace in Boulder, Colorado.

The COSTAR concept originated with the late Dr. Murk Bottema, a renowned optics engineer who worked at Ball Aerospace, and the HST Strategy Panel, a group of scientists and engineers whose charter was to recommend plans to recover HST's performance potential. COSTAR meets the requirements they developed for a feasible, cost-effective optical correction that could be implemented during HST's first scheduled servicing mission.

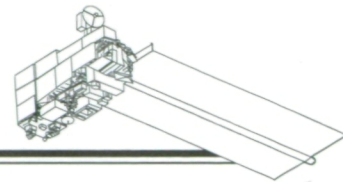
In principle, spherical aberration can be corrected by numerous methods. Indeed, the HST Strategy Panel considered dozens of ways to correct HST's aberration. Their solution was to create a new "instrument" which would be installed into the HST by astronauts to deploy corrective optics for the remaining axial scientific instruments. COSTAR replaces the High Speed Photometer (HSP), the least utilized scientific instrument on board the HST, and rectifies the aberrated wavefront of light entering the Faint Object Camera (FOC), the Goddard High-Resolution Spectrograph (GHRS), and the Faint Object Spectrograph (FOS) scientific instruments. The original HST observing schedule was modified to allow scientists to complete most of the planned research involving the HSP prior to installing COSTAR so that when COSTAR is installed (and the HSP removed), impact to the overall science mission would be minimized.

COSTAR is about 7 feet (ft) long and 3 ft square, and weighs about 660 pounds (see the first figure). It consumes approximately 60 watts of electrical power, is composed of roughly 5,300 parts, and has a minimum design life of 5 years. It cost some \$50 million to design, build, and test. COSTAR will place pairs of small mirrors in front of the FOC, GHRS, and FOS instruments. The mirrors are carried on a DOB that extends from the COSTAR enclosure after it is installed into the HST. The first mir-



Cutaway view of the COSTAR instrument.

rors in each pair, called M1 mirrors, intercept the light from the HST secondary mirror and reflect it to the second, or M2 mirrors, which then reflect the corrected light into the instrument apertures. The M1s have relatively simple spherical figures; they project an image of the entrance pupil (i.e., the HST primary mirror) onto the M2s.



The M2s are shaped with complex prescriptions that cancel the spherical aberration generated by the HST primary mirror. The M2s also block the views that the scientific instruments have of the HST secondary mirror so that the instruments see only unaberrated light coming from the COSTAR (see the second figure). The technical challenges of COSTAR have been driven by stringent optical alignment and throughput requirements, and the need for a design that would be practicable within the HST servicing framework. Optical alignment must be exact and repeatable through deployment operations, yet it must also be adjustable in orbit to compensate for locational uncertainties and allow for image optimization. Ultra-low-expansion graphite-epoxy optical benches, stiff beryllium arms, precision fittings and motors, and tight thermal control subsystems are necessary to keep alignment stable. The optics must be extremely precise in surface figure, very clean, and highly reflective over a wide band of wavelengths, including UV. What are likely the best reflective coatings ever produced were deposited onto the COSTAR mirrors by the Optics Branch at GSFC. All materials, parts, and components have been painstakingly cleaned to mini-

mize contamination that could degrade optical throughput, especially at the scientifically important and easily absorbed UV wavelengths. Lastly, the DOB, containing all of the mirrors and their mechanisms, must deploy through a small, 6-inch by 4-inch triangular opening at the inner corner of the COSTAR enclosure without interfering with other hardware on the HST. The combination of such difficult requirements made COSTAR a notable technical challenge.

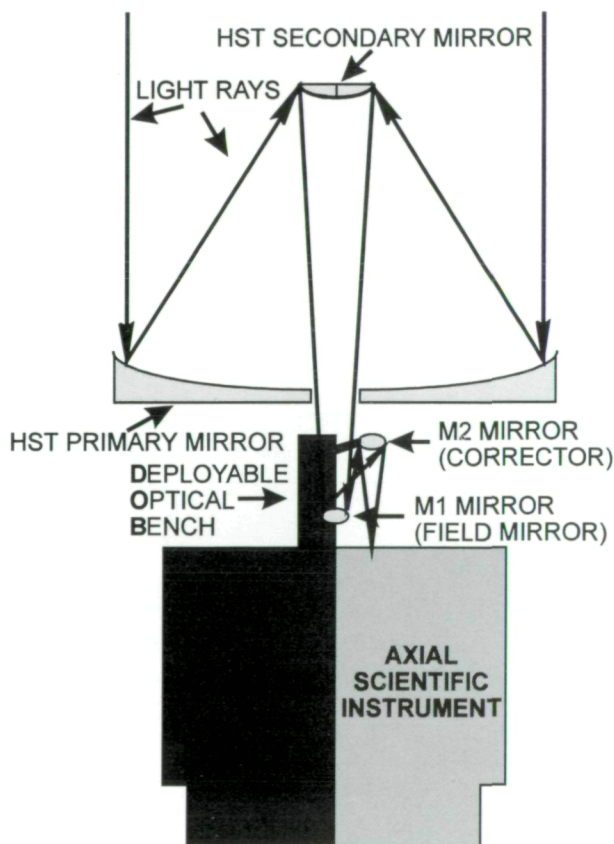
The tight schedule—28 months from concept to delivery—made for a significant management challenge and added a new dimension to COSTAR's technical complexity, and the pressure to make sure that COSTAR works correctly has been intense. To avoid the same mistakes that caused the wrong prescription to be built into the HST primary mirror (and that left it undetected before launch), the COSTAR was built and aligned using the COSTAR Alignment System (CAS), and verified using an independent tool, a model of the HST Optical Telescope Assembly (OTA) called the Refractive Aberrated Simulator/Hubble Opto-Mechanical Simulator (RAS/HOMS). Given that its construction was independent of its verification, the probability that the COSTAR corrections would be in error is virtually zero. However, further steps will ensure that COSTAR will function as planned. The RAS/HOMS itself has been verified independently in multiple ways to make sure it is representative of the HST, and the Faint Object Camera-Structural Thermal Model (FOC-STM), essentially a twin of the real flight FOC on orbit, was used to help verify COSTAR's performance. Lastly, a team of GSFC and contractor optical engineers (known as the Independent Verification Team (IVT)) built their own hardware, which they used to verify the performance of the RAS/HOMS and the COSTAR.

The COSTAR program has been an exciting, fast-paced team effort. The reward for hard work and perseverance will be the realization of HST's first-generation potential and promise, and the knowledge of a job well done.

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COSTAR optical correction concept.

HST REAL-TIME GROUND SYSTEM FOR THE HST FSM

THE HST FSM features an ambitious plan where major components of the HST will be replaced on-orbit by shuttle astronauts during 5 days of EVA. The replacement hardware includes: solar arrays, rate sensor units, the WF/PC-II, COSTAR, an on-board computer coprocessor, and other replacement units. During EVA, the HST will undergo a succession of hardware configuration changes as the astronaut crew installs the replacement items.

Typically, after a replacement hardware item is installed and while the EVA is still in progress, an "aliveness" test is executed to verify the health of the new component. Following the aliveness test, a hardware functional test is conducted. In order to accomplish the aliveness and functional tests, the HST real-time ground system must quickly adapt to the changing HST hardware configuration. The design of the HST real-time ground system must support a changing spacecraft configuration, starting with the initial HST configuration, ending with the final HST configuration at deployment, and all steps in between. Thus far, GSFC control center real-time applications, including the initial HST Project Operations Real-Time System (PORTS) used to support the first 3-plus years of HST operations, were required to support only a fixed complement of spacecraft hardware. The Payload Operations Control Center (POCC) Refurbishment System (PRS), in conjunction with the HST Project database, was designed and built to meet the unique requirements of the HST FSM. The design of the HST PRS required major changes to the PORTS baseline design to support FSM requirements. Foremost is the requirement to rapidly (on the order of 1 minute) respond to the HST spacecraft configuration changes. To meet this requirement, the PRS was designed as an expansion of the original HST PORTS system.

The PRS provides the functional capability to conduct HST real-time operations, including: HST health and safety monitoring, HST real-time commanding, and engineering telemetry data processing and display. Integrated with the PRS is a set of files that defines HST command and engineering telemetry data definitions and formats. The command and engineering telemetry data are organized by the HST spacecraft subsystem, where all information needed to operate each subsystem is specified. This information is managed in a set of files within the HST Project Database (PDB). The PRS requires the information contained in the PDB to perform its real-time functions.

To support the HST FSM, a new scheme was required by the HST PRS to apply PDB-supplied command and te-

lemetry information. The PRS maintains internal files derived from the PDB command and telemetry files for all HST spacecraft subsystems, both those currently on board the HST flight system and those that are included in the flight inventory for the FSM. As a result, PRS contains internal command and telemetry processing tables that are significantly larger than those of the original PORTS design. This led to increased system performance requirements, which were met by the development of the PRS distributed architecture (see *Practical Application of Real-Time Distributed Processing Concepts on the Hubble Space Telescope Ground System*, in this volume). The key PRS design feature that fulfills the FSM requirements is the capability to lock and unlock portions of the command and telemetry tables, thereby allowing reallocation of the active portion of those tables to meet the timeline requirements of the EVA sequences. Since the control is managed at the subsystem level, the PRS design can accommodate the changeout of spacecraft hardware in any order, and is not dependent on any specific spacecraft hardware configuration. PRS was delivered, tested, and installed into the operational HST ground system on June 26, 1993, replacing the PORTS. PRS has successfully supported ongoing HST operations since that time and is in place to support the FSM. In preparing for the HST FSM, the PRS has been utilized by HST operations personnel during multiple FSM simulations to execute the planned operational EVA timeline. The PRS design features to support these activities have performed extremely well, demonstrating that the system will meet the demands of the HST FSM.

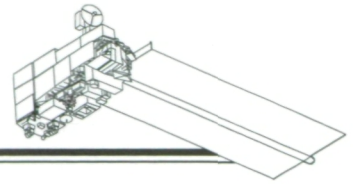
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THE CHALLENGE OF GOES PERFORMANCE VERIFICATION

AT NASA, the ideal preparation of spacecraft systems for launch has always included an end-to-end demonstration in systems ground test of the capability to meet performance requirements under conditions that simulate factors adversely affecting on-orbit performance. Measured performance is then indicative of what can be expected in flight. However, present-day systems have become so complex, and the number of factors adversely affecting the performance so numerous, that it is often not possible to perform a true end-to-end test. This is the situation with the GOES I/M spacecraft series being developed by GSFC for the National Oceanic and Atmospheric Administration (NOAA). The first of this series, GOES-I, is to be launched during the second quarter of 1994. The figure shows the deployed configuration of the GOES-I satellite.

The verification problem stems from the demanding requirements for radiometric accuracy and position determination of the visible and infrared data returned from the primary Imager and Sounder instruments. The accuracy of the brightness temperature of the scene inferred from Imager and Sounder data is specified at 1 Kelvin, requiring accurate in-flight calibration as well as precise ground characterization of channel non-linearities for correction of the flight data. Image Navigation and Registration (INR) requires real-time knowledge of the location of the imaged pixel to within 4 km at the subsatellite point on the surface of the Earth. This implies absolute knowledge of the centroid of the instantaneous field of view in each spectral channel to an accuracy of 22 arcsec. Corresponding pixels in successive image frames 15 minutes apart are required to be coregistered in object space to within 1.5 km, or less than 10 arcsec in Earth-referenced look angle. Orbital effects are to be corrected by Image Motion Compensation (IMC) so that the data always appear to have been obtained from a perfect, zero-inclination orbit. In the face of such requirements, environmental factors which might normally be benign become threats to system performance.

Several extraordinary measures in instrument and spacecraft systems design have been necessary to meet these and other demanding requirements. The spacecraft three-axis stabilization chosen to improve the radiometric performance of the Imager and Sounder produces thermal gradients and thermal distortion in the spacecraft and instruments which directly affect the instrument performance in INR. The requirement for real-time knowledge

of the pointing angle in the presence of thermal distortion can only be met by *a priori* knowledge of the expected distortion. This knowledge will be obtained by measuring the distortions which occurred during the previous day. Satisfying the requirements for orbit correction and frame-to-frame registration is then accomplished by actively steering the instrument's scan mirror to correct for the orbit ephemeris and system thermal distortion. This process is referred to as IMC. Much effort has been devoted to improving the performance of the Earth sensors and improving the thermal design/modeling of the spacecraft and Imager/Sounder instruments in order to understand and minimize pointing errors due to thermal distortion. Accurate sensing of stars and landmarks by the Imager and Sounder is required to independently determine the scan mirror pointing corrections. Further, the INR function is required throughout the diurnal cycle, so that detection of stars close to the Sun as well as to the sunlit Earth can be performed.

The GOES-I system, given the pointing requirements, can tolerate very little spacecraft jitter. Jitter in the optical instruments' line-of-sight, which results from dynamic interaction with the spacecraft's moving parts, must be either corrected for or tightly controlled. The spacecraft components generating the major mechanical disturbances to the system are the momentum and reaction wheels, the scan mechanisms in the Imager and Sounder, the solar array, and the x-ray positioner on the solar array. The scan mirrors, in particular, when they execute a 180° rotation to their internal calibration targets, cause significant disturbance and nutation to the momentum-biased system, which must be sensed and corrected for to meet the pointing requirements. The corrections, called Mirror Motion Compensation (MMC), are computed autonomously by the spacecraft Attitude and Orbit Control System (AOCS) and added to the IMC correction. Since the corrections are dependent on the spacecraft inertia matrix, which varies in orbit as expendable fuel is consumed, the matrix must be observable in flight. This is accomplished by sensitive measurements of motion after an attitude disturbance. Concerns that the momentum wheels may interact with the Earth sensor's resonantly mounted scan mirror or the finely tuned instrument scan mirror servomechanisms must also be addressed by the test program.

The necessity for observing dynamic disturbances, both on the ground and in flight, was recognized early, and

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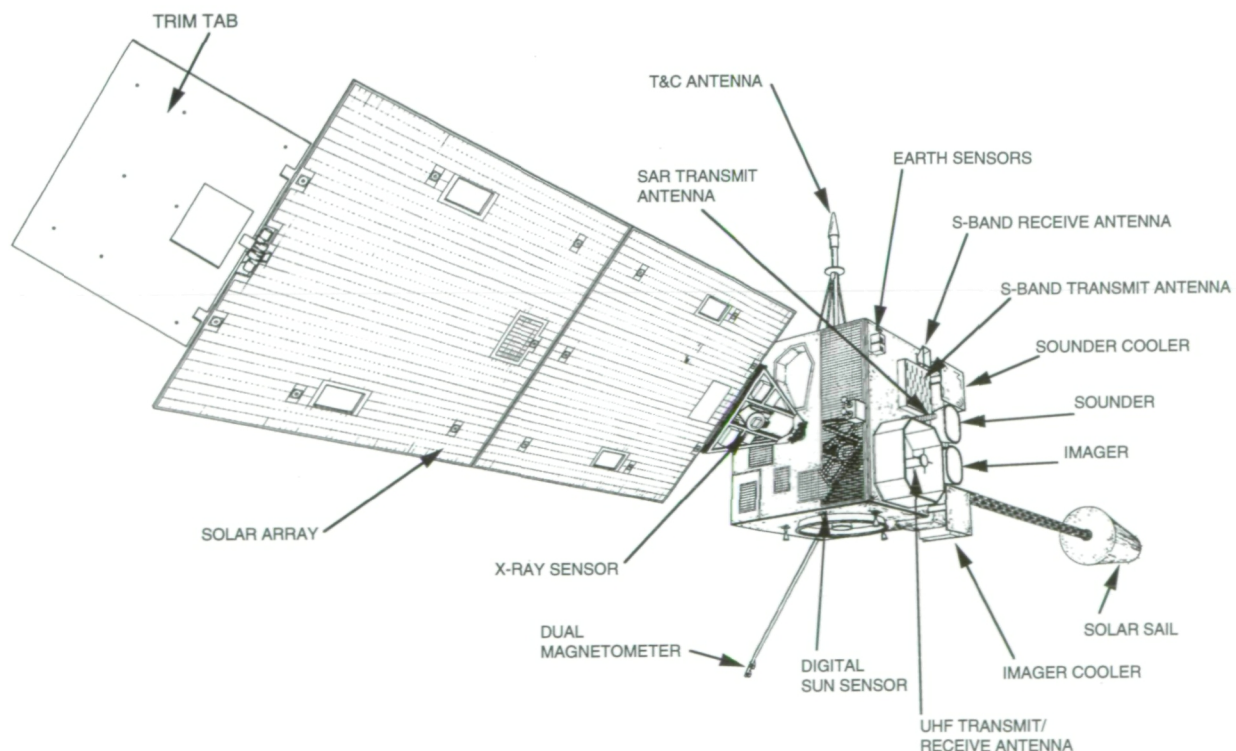
resulted in the incorporation into the spacecraft of an Angular Displacement Sensor (ADS) to augment the existing gyro package in the Digital Integrating Rate Assembly (DIRA). In addition, a multi-use data link was added to provide high-temporal-resolution observations of the ADS and DIRA.

The GOES Project at GSFC was faced with the complexity of the verification problem and increased emphasis on experimental verification of performance expectations. A multifaceted test program to augment the normal instrument and spacecraft acceptance test was established to gain confidence that the system on-orbit performance will be as designed. The major factors in performance addressed by the augmented test program were: (1) validation of the thermal models of the instruments in simulated solar environments; (2) star sensing in the presence of scattered light; (3) measurement and characterization of dynamic interaction; and (4) use of a wide-field collimator to produce an image product in an end-to-end test configuration for the Imager, and to verify Imager scan linearity performance.

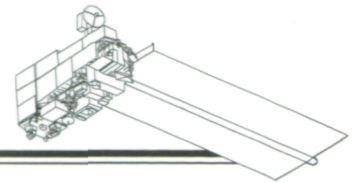
Thermal effects of exposure of the instruments to the 24-hour solar rotation cycle are clearly critical to all aspects

of GOES system performance. As the program developed, analysis showed that optical and radiometric performance would be greatly affected by the expected diurnally varying temperature gradients. Changes were implemented to the thermal and structural design of the scan mirrors, which receive the brunt of the solar input, but the apparent sensitivity of instrument performance to the thermal behavior caused such concern that the GOES Project implemented a solar simulation test of the Imager to validate the thermal model used for prediction and to demonstrate fundamental optical and radiometric performance in the presence of the diurnal solar cycle. As a result of this test, further improvements to the thermal design have been implemented and the thermal model for the instrument has been improved and validated. The increased confidence in the on-orbit performance gained has prompted the GOES Project to test the Sounder in the solar beam environment as well.

Ground verification of the star-sensing capability in the presence of stray sunlight places constraints on the test configuration which are not compatible with other test environments (such as thermal vacuum testing) where multiple scattering sources are unavoidable. To verify the star-sensing capability, a special test was performed with



The deployed configuration of the GOES-I satellite.



a star simulator (collimator) while a solar simulator moved along an arc in front of the instruments. A "black hole" space clamp target was provided above the collimator line-of-sight to provide a zero reference. Even though limited by line-frequency photon noise in the solar simulator, the test demonstrated a star detection capability more than adequate for the GOES mission.

To fill the need for a means of spacecraft-level testing for dynamic interaction and scan linearity, a special Wide Field Collimator was developed which could present a nearly full field-of-regard image to the instruments. Acceptable image quality is maintained over the full field of regard of the GOES instruments, and when used in a mosaic manner with a precise and calibrated scan linearity target in the collimator focal plane, full-field performance of the scanner can be determined in the presence of dynamic disturbance.

In summary, the test program described above accomplished its objective of determining instrument system end-to-end performance in a laboratory environment. The GOES test and evaluation program has been expanded to incorporate all known adverse effects into the end product by computer simulation. A comprehensive model of both pointing and radiometric performance has been constructed, which is used to study system performance statistically and is being extended to the generation of data products, including simulated images, with known errors injected.

Notwithstanding the difficulties associated with performance verification for the GOES mission, the verification program implemented by the GOES Project provides a substitute "end-to-end" test which establishes confidence that GOES-I, as designed, will meet its basic performance requirements in orbit. For this series of spacecraft, the preview of performance gained has been invaluable in revealing areas where system performance margins might be improved. This would avoid some of the modifications to the series which might result were the first "end-to-end" performance evaluation to be on GOES-I in orbit.

Many organizations and individuals have contributed to the implementation of this verification program under the direction of the GOES Project Office at GSFC. The organizations include GSFC-based entities and contractors for the construction of the instruments, spacecraft, and test facilities. The computer simulation of system end-to-end performance was done by Swales and Associates, Beltsville, Maryland, under the direction of the Mechanical Systems Division at GSFC.

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Mr. Arthur Obenschain is the Project Manager on the GOES Project. He earned his BSEE from the University of Maryland. Mr. Obenschain has been at GSFC for 27 years, and he received the NASA Exceptional Service Medal for his work on the GRO Project and the GSFC Award of Merit for his leadership of the GOES Project.

GRAVITY AND MAGNETIC EARTH SURVEYOR

THE GRAVITY AND Magnetic Earth Surveyor (GAMES) will provide a comprehensive map of the gravity and magnetic fields of our Earth. A satellite mission concept has been developed and studied that will measure these Earth properties to a higher resolution than has previously been possible. The gravity and magnetic field data obtained from this mission will enable the mapping and study of absolute circulation within the oceans. Using GAMES gravity field data in conjunction with altimeter satellite measurements at the height of the sea surface, it will be possible to measure these currents and their changes with time, and to see how these changes affect the redistribution of heat within the oceans. This is critical for understanding global weather and climate change.

The vastly improved resolution of gravity field data also will support dynamic modeling studies of important Earth structures: rifts where continents split apart; folded mountains where continents rejoin; large basins where petroleum and ore deposits collect; and submarine trenches, where ocean crust is recycled back into the hotter mantle. Crustal magnetic field data complement the gravity data, refining our knowledge of the composition and subsurface temperature state of these structures.

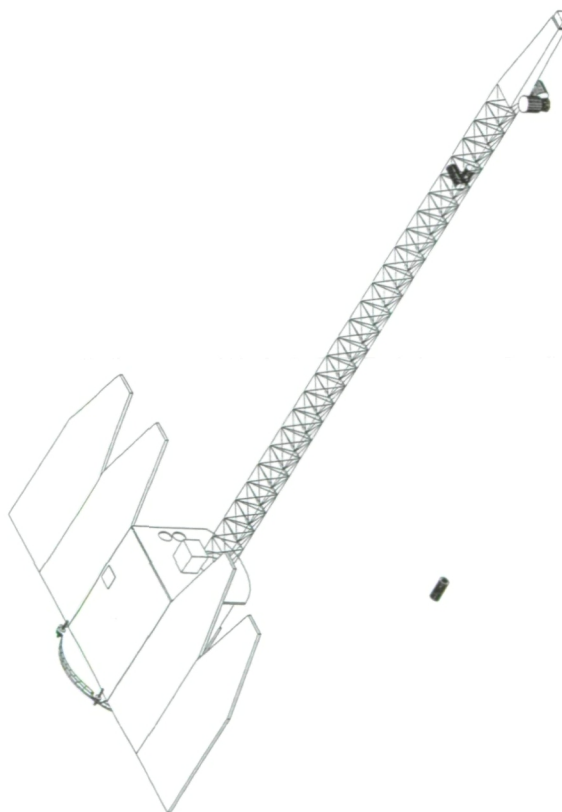
Data from GAMES will reveal processes at work in the interior of the Earth, where fluid motions in the outer core generate the magnetic field and where moving cells in the mantle drive motions in the lithospheric plates of the Earth. GAMES will help us study and understand these processes and others, including how the crust rebounds from the loss of Ice Age glaciers.

The instruments on board the GAMES spacecraft (see the first figure) are in two functional groups, one for magnetic sensing and one for gravity measurements. The magnetic sensors are located on a boom to isolate them from the magnetic field of the GAMES spacecraft. There are two sensors for this mission: a Scalar Magnetometer and a Vector Magnetometer. In addition to the isolation boom, the equipment that supports these sensors includes star cameras and a metering structure for vector pointing knowledge.

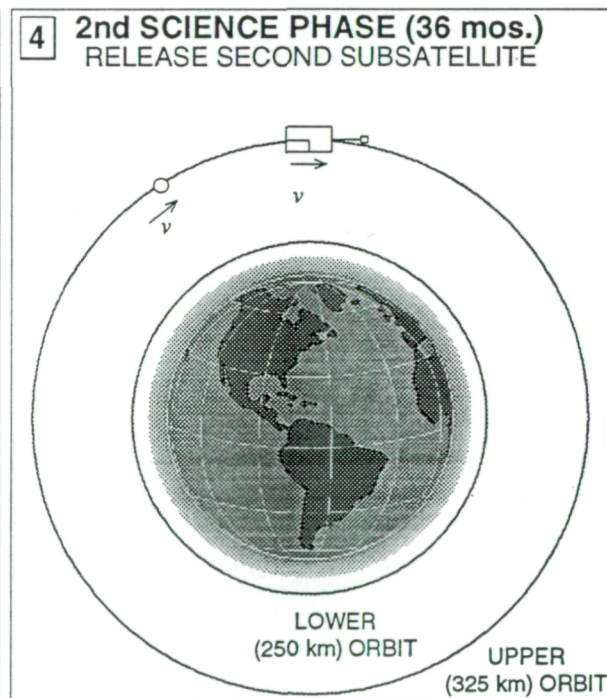
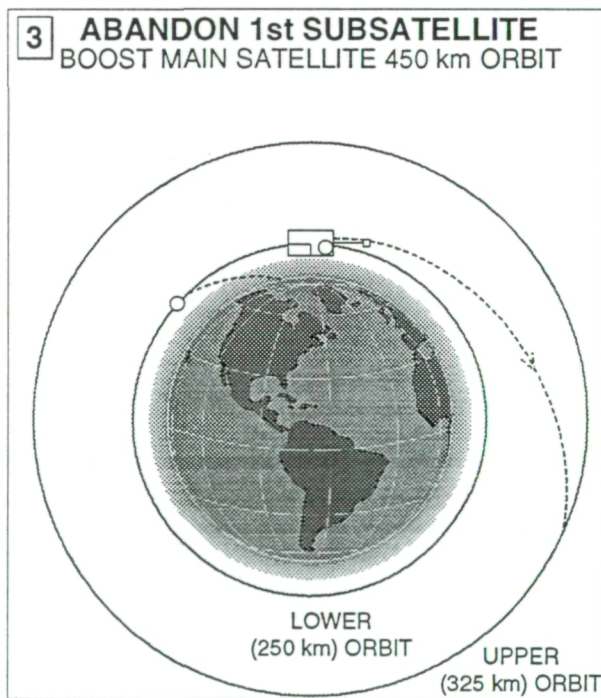
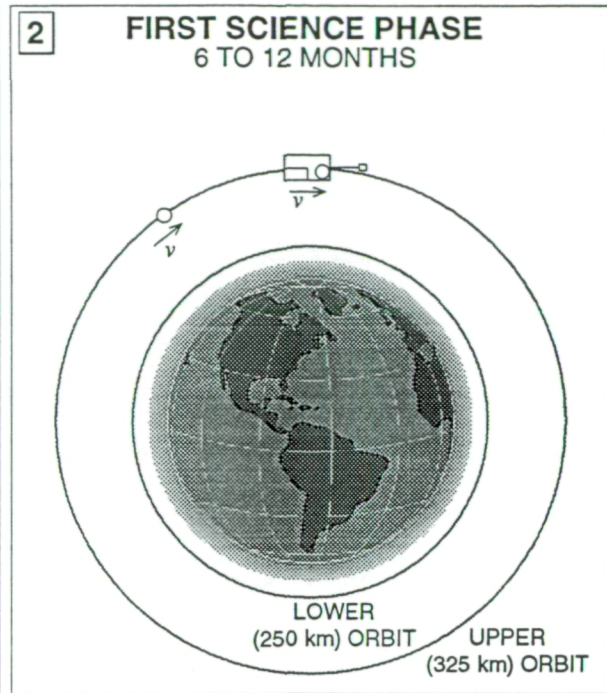
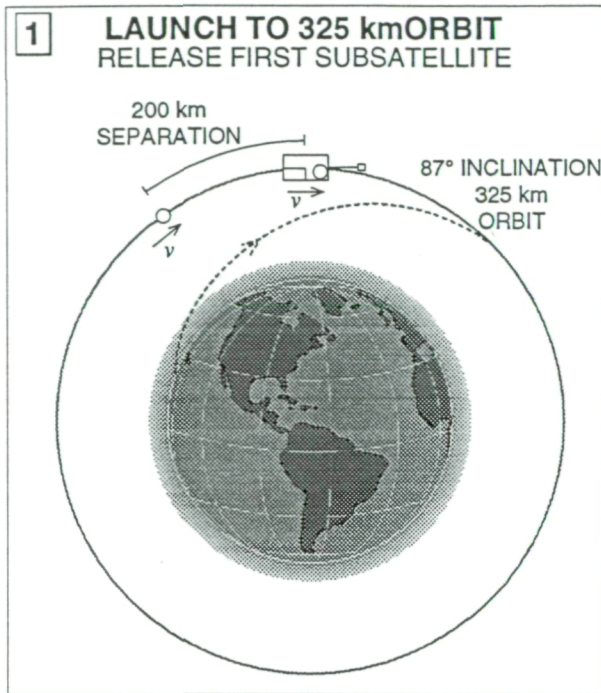
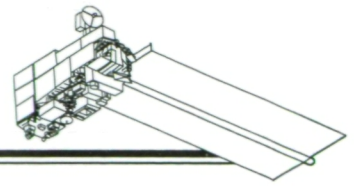
The instruments that provide gravity field measurement do so by measuring accelerations. Variations in the gravity field can be detected through accurate knowledge of the spacecraft's motion over time. To measure these, a Global Positioning System receiver provides spacecraft

velocity information to an accuracy of 5 cm/s. Measurements of atmospheric drag are also made with a highly accurate accelerometer and used to correct motion data so that only gravity is being mapped.

Measurements of closely spaced gravity differences are made by measuring the changing velocity between the two satellites. The two satellites, separated from each other while occupying the same orbit, will each experience velocity changes as they pass in turn over local gravity field changes. When data are collected, a gravity map of the entire Earth can be constructed. To accomplish these measurements, the Laser Ranging Instrument (LRI) will detect small velocity changes between the main satellite and the target subsatellite 200 km away. The LRI will be able to detect relative velocity changes between the main spacecraft and the subsatellite to an accuracy of better than 0.1 mm/s.



The Gravity and Magnetic Earth Surveyor (GAMES).



GAMES Mission Profile.

FLIGHT PROJECTS

After GAMES has established its initial working orbit, a subsatellite will be released. The two satellites will move apart over several days. When the proper separation is achieved, the main spacecraft uses its propulsion system to match orbits with the subsatellite and ranging operations begin. All data are stored on board the main spacecraft and transmitted to the ground twice per day. Every time the satellites begin to get too far apart, an orbit adjustment maneuver is made to match orbit altitudes and eccentricities while maintaining satellite separation within tolerance.

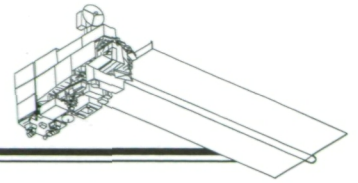
Planning the GAMES mission profile is strongly influenced by the expected increase of solar activity and the resulting increase in upper atmospheric density. The present concept, illustrated in the second figure, is to release a subsatellite at 325 km and follow its orbit decay to approximately 250 km. This will take 6 to 12 months. By this time, most of the GAMES mission objectives will be achieved. The main satellite then abandons the subsatellite and boosts itself to 450 km. A second subsatellite is then released and again it is followed down to 250 km. This mission phase can take an additional 3 years. The

flexibility provided by an on-board propulsion system and two subsatellites allows changes to this profile through launch and until the subsatellite is actually released. Data from GAMES will be processed into products of ever-increasing detail and accuracy as the information is accumulated and correlated with other sources.

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Sponsor: Office of Mission to Planet Earth

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DEVELOPMENT OF S-BAND AND Ku-BAND GaAs FIELD EFFECT TRANSISTOR SOLID-STATE POWER AMPLIFIERS FOR TDRS

THE TDRS PROJECT OFFICE successfully undertook a program to develop Ku-band and S-band solid-state power amplifiers (SSPAs) for the TDRS Flight-7 spacecraft. TDRS F-7 will utilize four Ku-band SSPAs in the K-Band Single-Access Forward Service, and four S-band SSPAs in the S-band Single-Access Forward Service. These SSPAs replaced the traveling wave tube amplifiers (TWTAs) found in previous TDRSs. The primary reason for this substitution was to improve reliability.

The TRW-designed Ku-band SSPA is based on space-qualified gallium-arsenide (GaAs) metal semiconductor field-effect transistor (MESFET) technology from Raytheon, NEC, and Fujitsu. The MESFETs were procured as unpackaged chips and assembled in hermetically sealed packages utilizing radio-frequency (RF) hybrid construction techniques. All modules utilized alumina substrates attached with a gold-germanium eutectic system; component attachment and RF feedthrough installation employed a gold-tin eutectic system. These modules contain the MESFETs, Schottky diodes, P-type/intrinsic-N (PIN) diodes, transmission lines, feedthroughs, and capacitors necessary to provide amplification at 13.775 GHz.

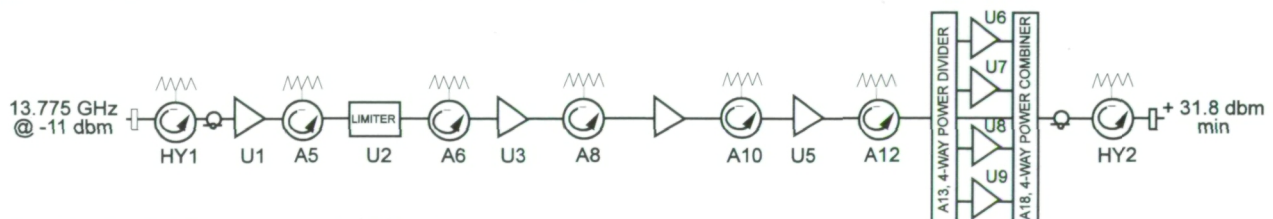
The amplifier (see block diagram in the first figure) consists of four stages of RF modules in cascade, driving four modules in parallel to give the required output power of +31.8 dBm minimum at beginning-of-life (BOL) and +31.0 dBm minimum at end-of-life (EOL). The RF modules are mounted in an aluminum housing and interconnected by 50-ohm microstrip lines. The microstrip lines provide some tuning capability to the amplifier when the RF modules are integrated. The amplifier has a waveguide interface, and low-loss isolators are used to provide isolation and low-voltage standing-wave ratio (VSWR). The output isolators can take the total reflected RF power in the event that the SSPA is turned on without a proper termination. Limiter modules are used to meet the input power range and to control the RF drive to the output

power FETs. Temperature compensation is provided by using a PIN diode attenuator controlled by temperature-monitoring circuitry. The SSPA provides telemetry points for the RF output power, DC voltages, and baseplate temperature.

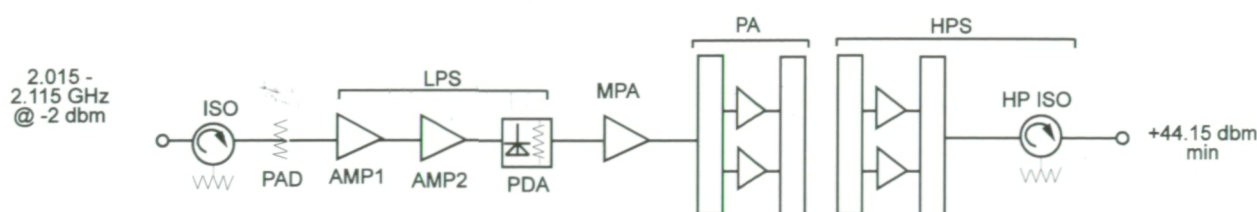
NASA imposed a strict qualification and screening program of RF and DC testing. The test regimen was tailored to the flight history, reliability considerations, and available qualification history. The Ku-band SSPA utilizes two pairs of Raytheon RPK2024 GaAs MESFETs, each fed by a 3-dB coupler for the balanced output stage. The driver stages utilize NEC 900100 and Fujitsu FLK-012XP GaAs MESFETs. The life test for the RPK2024 was continued until 4 of 6 devices failed at each temperature. The results were used for an Arrhenius prediction for these devices. In addition to the above chip-level qualification tests, each RF module passed 320 hours of RF burn-in at a channel temperature of 60 °C; samples of each type passed 1,000 hours of life test under the same conditions. The amplifiers were manufactured by TRW at their Redondo Beach, CA facility.

The S-band SSPA amplifier is also based on space-qualified GaAs MESFET technology. The amplifier operates in the frequency range from 2.015 to 2.115 GHz.

The amplifier (see the block diagram in the second figure) consists of three sections of RF modules in cascade, driving the output section to give the required output power of +44.15 dBm minimum at EOL. Actual SSPA output power averages 30 W. The RF sections are mounted in an aluminum housing, and interconnected by 50-ohm microstrip lines. The amplifier has a coaxial connector interface, and low-loss isolators are used to provide isolation and low VSWR. The output isolator can handle the total reflected RF power in the event that the SSPA is inadvertently turned on without a proper termination. Temperature compensation is provided by using a PIN diode attenuator and a thermistor network. The NEC fac-



Ku-Band Solid-State Power Amplifier.



S-Band Solid-State Power Amplifier.

tory in Yokohama, Japan, demonstrated excellent capabilities in all areas of manufacturing and testing. Their internal workmanship standards met NASA workmanship requirements, and their personnel were extremely well trained, disciplined, and cooperative at all levels of management, technical staff, and floor operations activities. The amplifier's output section uses two NEC NES1723-20B devices in parallel to meet the output power requirement. This 1- μ m gate length GaAs MESFET has a power output capability of 20 watts with input and output sections partially matched to 50 ohms over the specified frequency range. The low-power amplifier section uses an input isolator followed by a pair of hybrid balanced amplifiers based on the NE673 GaAs FET transistors. The amplifiers are followed by a PIN diode attenuator hybrid. This hybrid uses the ND6886 PIN diode in a balanced configuration to provide small-signal gain control. The second stage of the balanced amplifier hybrids operate as an active limiter. This amplifier stage is set at the 14-dB compression point in the overdrive mode, and at the 9-dB compression point in the saturated mode according to the worst-case analysis. The NE673 devices were life-tested at the 15-dB compression point for margin. The medium-power amplifier (MPA) uses a NE800196 to drive the power amplifier/driver amplifier (PA) stage. The PA stage uses a balanced design with a pair of NE800496 devices. Detailed worst-case analyses for all amplifier stages and the entire SSPA chain were performed by the NEC/TRW/NASA team. These analyses were utilized for a variety of purposes, including estimation of EOL SSPA performance, determination of BOL operating points for each stage, and risk assessment/management. The results of the worst-case analyses were critical to the closure of the design phase of the program. Due to system constraints in the S-band Single Access Forward channel, tight upper and lower boundaries were placed on the BOL SSPA output power. NEC did a superior job in selecting 1723 MESFET devices for gain and output power, gain flatness, third-order intermodulation performance, and DC operating points. NEC also did an excellent job in controlling the drive from the MPA and PA stages to the high-power output stage, thus limiting the overdrive of the 1723 power MESFETs, and enhancing the reliability of the SSPA

design. The worst-case EOL compression of these high-power devices is limited to 1.5 dB. Because of the criticality of the S-band service for Shuttle communication and a reliability problem known as "power slump," which was observed with power GaAs MESFET from a different supplier, NASA and TRW devised a series of reliability tests to eliminate these concerns with the 1723. The qualification tests were devised to provide a margin of safety of 1 dB over worst-case RF drive levels, and 500 millivolts of margin over the worst-case drain bias conditions. The results from these tests complement over 13,000 hours of DC life test previously performed by NEC.

In summary, the TDRS Project Office successfully managed the transition from TWTA to SSPA in two critical applications. Important lessons were learned in the areas of SSPA design evaluation, MESFET failure mechanisms, and SSPA requirements analysis. Future plans include investigations into GaAs MESFETs and pseudomorphic High Electron Mobility Transistors (P-HEMTs) for power amplifier and low-noise amplifier applications at Ku-band, Ka-band, and W-band frequencies. The authors wish to acknowledge the support and contributions made by Charles Vanek (TDRS Project Manager), and Michael Kerrigan (TRW Payload Manager) on this effort.

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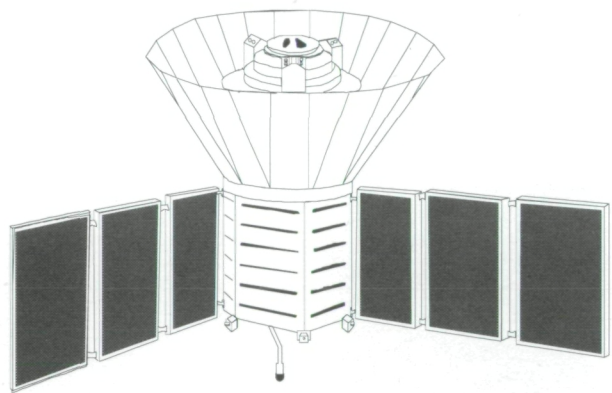
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Sponsor: Office of Space Communications

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SPACE SCIENCES





ROSAT observations of a sparsely populated group of galaxies have revealed that this system has a 25:1 ratio of dark matter to baryonic matter (the visible stuff), larger by a factor of 2 to 3 than any other system yet studied. This is the first object for which the observed ratio of dark matter to baryons is consistent with inflation and Big Bang nucleosynthesis.

*(Mulchaey, J. S., D. S. Davis, R. F. Mushotzky, D. Burstein, 1993, Ap. J. Lett., **404**:L9).*



SPACE SCIENCES

GODDARD SPACE FLIGHT CENTER is privileged to have a role as a prime focal point for astrophysics and space physics investigations from spaceborne platforms. Astrophysical observations from above the Earth's atmosphere sample broad bands of the electromagnetic spectrum invisible to terrestrial instruments. In addition, *in situ* measurements of particles and fields give insights into magnetic and plasma phenomena throughout the Solar System. Subsequent data analysis and modeling efforts lead to a more comprehensive understanding of the history and evolution of the Universe and its constituents.

Cosmology

Following the Cosmic Background Explorer's (COBE's) tremendous early successes, continued data collection and analysis brought several significant findings in 1993. First, the spectral shape and temperature of the Cosmic Microwave Background Radiation (CMBR) from the Big Bang was measured to unprecedented accuracy. This not only confirmed the hot Big Bang origin of the Universe, but also showed that virtually all of the energy in the CMBR was injected before the Universe was 1 year old. As a consequence, previously postulated theories of cosmic strings or of dark matter which release energy over long periods of time are ruled out. Second, the CMBR temperature and density fluctuations revealed last year by COBE were confirmed as genuine features of the Big Bang itself. These early fluctuations are undoubtedly the seeds of currently existing large-scale structures in the Universe. Finally, the balloon-borne Medium-Scale Anisotropy Measurement project extended observations of these fluctuations to smaller spatial scales than could be detected by COBE, and, in the process, found two unexpected point sources of microwave radiation. If they are part of the CMBR, these sources pose serious challenges to the expected size distribution of CMBR fluctuations; if not, they may be previously undetected foreground objects which could interfere with accurate CMBR measurements on the smallest spatial scales.

High-Energy Investigations

GSFC-based high-energy astrophysics research in 1993 was dominated by the continued successes of the x-ray Röntgen Satellite (ROSAT) and of the Compton Gamma-Ray Observatory (CGRO).

ROSAT observations of diffuse x-ray sources spanned spatial scales from the Galactic to the cosmological. In our own galaxy, they provided definitive evidence of a massive halo, revealed by warm dust clouds shadowed against the soft Galactic x-ray background. In other galaxies, they detected a massive halo engulfing a small group of only two galaxies. If this phenomenon is common, it suggests that there may be enough mass tied up in individual galactic halos to stop the expansion of the Universe. The hot x-ray-emitting gas known to pervade clusters of galaxies was shown to have structure—perhaps indicative of subclusters of galaxies agglomerating to form larger clusters of galaxies. A careful spectral analysis of the general extragalactic x-ray background suggested that the sources of this background emission are numerous active galactic nuclei and x-ray-emitting galaxies too weak to be detected individually.

Among the individual sources that ROSAT surveyed was the supernova SN1993J in the galaxy M81. Here, continued ROSAT observations showed that the x-ray luminosity decreased much more slowly than was predicted by theoretical models. ROSAT also showed that the enigmatic gamma-ray source, Geminga, pulses in the x-ray region of the electromagnetic spectrum, indicating that it must be a neutron star.

In the gamma-ray region of the electromagnetic spectrum, a number of pulsars were observed by the CGRO's Energetic Gamma Ray Experiment Telescope (EGRET). These observations confirmed an earlier suspicion that older pulsars are far more efficient producers of gamma rays than are their younger counterparts. To better interpret these and other EGRET observations of discrete point sources, a detailed model

of the Galactic diffuse gamma-ray background emission was developed. This model gives a better understanding of the background emission and how it might interfere with observations of discrete objects. Perhaps the highlight of EGRET's year came on January 31, 1993, with the detection of the highest energy gamma-ray burst ever seen.

Monitoring gamma-ray bursts is the full-time job of CGRO's Burst and Transient Source Experiment (BATSE). With analyses of some 750 burst observations in hand, a longstanding mystery as to the location of gamma-ray bursters may have been solved. The observations are consistent with a burster distribution that is spherical (based on their spatial isotropy) and at cosmological distances with a redshift of $z \sim 1$ (based on the apparent time dilation of burst durations, the fact that weak bursts are undernumerous, and the absence of observed gravitational lensing of bursters by nearby galaxies). More precise burst source locations will soon be obtained through a project serendipitously made possible by the failure of CGRO's on-board tape recorders. With real-time data acquisition now required, an automated system is being developed in which the locations of gamma-ray bursters will be sequentially refined through near-simultaneous observations from three separate observatories: BATSE, the Goddard Geophysical and Astrophysical Observatory (GGAO) in Greenbelt, and the Rapidly Moving Telescope (RMT) on Kitt Peak. The planned sequence from gamma-ray detection by BATSE to final optical imaging by the RMT, including handing off of the location data from facility to facility, takes less than one minute.

Other 1993 high-energy highlights included the successful launch and initial observations of Astro-D, now known as the Advanced Satellite for Cosmology and Astrophysics (ASCA).

Stars and Galaxies

The magnetically active star AU Microscopium was the object of a detailed study by the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST). Redshifted Lyman-alpha emission was observed, indicative of stellar flare material moving down a magnetic loop, and iron emission lines (Fe XXI) indicating coronal temperatures ten times hotter than that of the Sun were detected.

A New Spectral Image Processing System (NEWSIPS) for the International Ultraviolet Explorer's (IUE's) extensive data archives is under development. By removing fixed-pattern detector noise from the IUE data, NEWSIPS is expected to reveal weak spectral features not recognized by the current IUE software. Prototype testing has already revealed a number of far-ultraviolet, high-excitation emission lines and Lyman-beta absorption features in the gravitationally lensed quasar 0957+561.

The common presumption that unseen dark matter is responsible for the observed anomalously high rotation velocities of stars in the outer reaches of galaxies was challenged by a model developed at GSFC using Weyl gravity potentials as an alternative to General Relativity. The fits of Weyl gravity models to observed galactic rotation curves are as good as the fits of dark matter models, but the Weyl models do not require arbitrary assumptions about the distribution of dark matter.

Solar System

Solar System studies in 1993 were highlighted by two interplanetary missions, two near-Earth environment missions, and the accompanying plasma and field modeling and diagnostics.

The Ulysses spacecraft, passing Jupiter en route to the Sun's south pole, located the sources of several Jovian radio emissions as being from the Io torus, from field lines passing through the torus, and from the Jovian auroral regions; it also discovered the existence of periodic radio bursts with occurrence rates strongly correlated to the solar wind velocity at Jupiter. Analyses of these observations allow them to be used as remote diagnostics of conditions in the Io/Jupiter source regions and of the solar wind velocity at Jupiter, respectively.

A tantalizing history of water on Venus was drawn from 14 years of Pioneer Venus Orbiter observations of the deuterium-to-hydrogen ratio in Venus' atmosphere. Both hydrogen and deuterium ions escape from Venus, but, since hydrogen escapes faster, the deuterium-to-hydrogen ratio increases as time goes on. Observations of the current ratio, coupled with careful modeling of the rates of escape, suggest a very large, early abundance of these vola-



tile materials. Assuming that the bulk of that now-lost hydrogen was once water, there may once have been as much as 340 times more water on Venus than currently exists in its atmosphere.

Closer to our own planet, the highly successful Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) was designed to observe the streams of high-velocity particles arriving at Earth from the Sun and from the interstellar medium. SAMPEX observed high-energy electrons from the Earth's magnetosphere as they penetrated the Earth's atmosphere. Coupling these observations with previous studies of the electrons' solar wind origins gave rise to models predicting their role in catalyzing reactions important to the global ozone balance. In another set of observations, SAMPEX located a new radiation belt, filled with high-energy ions from the interstellar medium, embedded in the lower of the two Van Allen belts.

Information to support our understanding of solar phenomena came from the April 8, 1993, launch of the Space Shuttle *Discovery* with a Spartan reusable carrier carrying two instruments designed to study the solar corona.

These instruments, the Ultraviolet Coronal Spectrometer (UVCS) and the White Light Coronagraph (WLC), spent 27 orbits successfully observing such large-scale coronal features as helmet streamers and polar coronal holes. In addition, a crucial study of the formation of the Solar 304 Å ionized-helium spectral line has been done using results obtained by the Solar Extreme Ultraviolet Telescope and Spectrograph (SERTS) rocket flight.

Insight into the interaction of solar-generated material with planetary magnetospheres came from a significant study of how magnetic reconnection actually occurs on a microscopic level. This promises new understanding of such processes as the penetration of solar winds into planetary magnetospheres and the ejection of plasmoids from magnetotail regions. GSFC researchers developed a model which directly addresses the particle scattering phenomena thought to underlie reconnection events. The scattering is encompassed by treating ions in the model as individual particles coupled to an electron fluid. The resultant two-dimensional hybrid code successfully simulated reconnection in idealized cases. Future work will attempt to simulate large-scale configurations more closely resembling the Earth's magnetotail.

Philip J. Sakimoto

COSMOLOGY

RIPPLES IN SPACE, THE ORIGIN OF STRUCTURES IN THE UNIVERSE

ONE OF THE FUNDAMENTAL MYSTERIES that we encounter in modern cosmology is the origin of larger astronomical objects that we can see in the sky today—galaxies and clusters of galaxies, the large “voids” in which galaxies seem to be lacking, the “walls” with a higher-than-average density of galaxies. While more traditional astronomy clarifies the detailed nature of these objects, the goal of cosmology is to understand the physical origin and evolution of the Universe on the largest of spatial scales, and how these objects came into existence. Recent data obtained by the Medium-Scale Anisotropy Measurement (MSAM) project and analyzed in conjunction with data obtained with the Goddard Space Flight Center’s (GSFC’s) Cosmic Background Explorer (COBE) instrumentation, provides insight about these processes and sets the stage for further work.

Einsteinian gravitation provides the theoretical basis for describing currently accepted cosmological scenarios. Coupled with certain key observations over the past 50 years (such as the Hubble expansion), we have used this general theory to create an outline of the major events in the history of the Universe. In particular, there is an initial event in which all the matter in the Universe is compressed into a very small region of space. From this region, the Universe expanded to become what it is today. This initial event can reasonably be defined as the “birth” of the Universe since, at that time, the Universe was so hot and dense that all information from any previous existence would have been erased. These physical conditions, and the subsequent rapid expansion, have led us to dub the initial event the “Big Bang.” The existence of the Big Bang also allows for defining the age of the Universe as the elapsed time since the event.

Depending on various details such as the total mass of the Universe, current estimates for this age run between 10 to 20 billion years. According to the standard scenarios, the objects that astronomers study have only been in existence for the past 5 billion years, a mere quarter to half of the age of the Universe. What happened in all that time between the Big Bang and the emergence of stars and galaxies? Is there a way to explain the distribution of mass in the Universe in terms of more fundamental physics? These are some of the challenges of modern cosmology.

The Cosmic Microwave Background Radiation (CMBR), discovered in the early 1960s, is a glow in the sky in the microwave and far-infrared regions of the electromagnetic spectrum (wavelengths of about 1 to 10 mm) which has a distribution of energy with wavelength that is typical of a system in thermal equilibrium. It was quickly established that the intensity of the CMBR with position in the sky is extremely uniform, exceeding the sensitivity of the early instruments which probed this uniformity at the 1-percent and 0.1-percent levels. Since that time, cosmologists have realized that measuring the spatial variations, or anisotropy, in this radiation would provide important clues to why matter is distributed the way it is today.

Imagine an extremely hot and dense Universe right at the initial Big Bang. The physical conditions are so far beyond currently understood physics that we cannot really describe the details of physical processes at that time. As the Universe expands and thus cools off (within the first few seconds), the density and temperature decrease sufficiently that we start to enter the regime of high-energy physics theory. This framework provides extrapolations based on measurements by the largest particle accelerators. Although the Universe is so hot that most common forms of matter are still in an undifferentiated state that resembles a “soup” of pure thermal energy, some elementary particles (e.g., protons, electrons) eventually condense out of this soup and become stable. As the cooling continues, atomic nuclei become stable until, eventually, hydrogen atoms can form. This happens when the Universe is approximately 300,000 years old. The critical event for this epoch is that photons (light), the major constituent of the primordial soup, start to behave independently from the matter in the Universe. During earlier times, the free electrons and protons interact strongly with the photons so they are, in a sense, all moving together as a well-blended cosmic soup. After the electrons are bound up with the protons to make hydrogen, the Universe becomes transparent to light, allowing the photons to propagate freely. For this reason, we name the event the era of *decoupling* (of matter from radiation). When we look deeply into the sky, this is the light that we see as the CMBR.



Because all the constituents (particles and radiation) in the early Universe interact strongly among themselves, they are in a special state called thermal equilibrium, for which the amount of energy at each wavelength (a spectrum) is predictable. As the Universe cools, the shape of this spectrum changes in a special way that is characteristic of cooler and cooler temperatures. We observe that the photons in the CMBR today have a distribution characteristic of 3 Kelvins (K), and, knowing that hydrogen atoms are stable at temperatures below about 3,000 K, we can predict that the epoch of decoupling occurred when the Universe was only 3/3000 or 1/1000th of its current size.

When we study the distribution of intensity of the CMBR in the sky, we are actually looking at the distribution of matter during the era of decoupling. This is like looking through a transparent Universe back to the time of decoupling, before which the Universe was opaque, like a dense fog. By studying the bright and dark spots of the radiation, we infer the pattern on the surface of the fog. In the case of the CMBR, the pattern is the distribution of matter. The regions that are slightly more dense than others gravitationally attract the photons a bit more and, in the expansion of the Universe, ultimately cause them to lose some energy and appear to be at a lower temperature. Those regions that are less dense have less of this effect, and the radiation appears to be at a relatively higher temperature. These small differences in matter distribution are the ripples in space which ultimately develop into the stars and galaxies we observe today.

There is one complication to this entire scenario which has only recently been plausibly explained. At each instant in the history of the Universe, there is a characteristic "radius" of the Universe which is set by the distance that light could have traveled since the birth of the Universe (recall that light travels at 300,000 km/s for all observers). Thus, if the Universe were only 1-s old, then we could not see things which are more than 300,000 kilometers (km) away; there has simply not been enough time for this light to propagate to us. Since no observer can see beyond this distance, the surface at this distance is also called the "horizon" for the observer. As the Universe ages, the horizon expands outward because there is more time for light from more distant places to travel to the observer.

An important side effect is that if we cannot see beyond the horizon, then neither can we be affected by any physical effect from beyond the horizon. Regions of space in

the Universe which are separated in distance by more than the horizon simply do not know about each other, and cannot influence each other's physical conditions. If we calculate the size of the horizon in the sky for the Universe at the epoch of decoupling, it turns out to be approximately 1° (about twice the angular diameter of the Moon). The fact that the spectrum and intensity of the CMBR are essentially the same for patches much larger than this size is very hard to explain, since our scenario does not allow these patches to communicate with each other and interact to determine their physical characteristics. A solution to this dilemma was found in the early 1980s and is called 'inflation' theory. The concept, motivated by a merging of high-energy particle physics theory with cosmology, is that within the first 10^{-34} s of the Big Bang, the Universe went through a period of extremely rapid expansion. This causes our entire Universe to be derived from a very small region of space (before inflation), which would have very uniform properties because it was small and its constituent parts could indeed communicate with each other. Thus, when we observe the CMBR from parts of the sky which are separated by more than 1° , the intensity variations are those imposed by the conditions in the pre-inflationary era (when the Universe was less than 10^{-34} s old!). After inflation, there is simply no way for physical processes to modify these variations. At angular sizes less than 1° , however, there has been sufficient time for physical interactions to modify the intensity of the CMBR at the epoch of decoupling, and the resulting variations in intensity depend on the details of the theory of such interactions.

Recently, GSFC's COBE satellite made some very fundamental measurements of the CMBR (see the next article in this volume). The Far Infrared Absolute Spectrophotometer (FIRAS) instrument determined that the spectrum matches the theoretical curve for thermal equilibrium to within 0.03 percent, lending unequivocal support to the Big Bang scenario, and confirming the belief that the early Universe was indeed in thermal equilibrium. The COBE/Differential Microwave Radiometer (DMR) instrument measured the anisotropy of the CMBR and made the first detection of the variations of CMBR intensity at the level of one part in 100,000 of the CMBR intensity. Both of these instruments have a beam size of 7° , which means that they can only see structures which are larger than about 14 Moon diameters in the sky. As noted above, any anisotropy measurement at resolutions coarser than 1° will probe the fundamental fluctuations from the pre-inflation era, but could not possibly be the

result of any interactions at a later time. It is also hard to relate these measurements directly to modern structures. The reason is that when we look at 7° size for a source at the distance of the era of decoupling, it corresponds to a size (after expanding by a factor of 1,000) larger than the largest of structures which we can see in the Universe today. The scale sizes on which we have data for the Universe today correspond to patches of only about 0.5° when we look back at the decoupling epoch. Thus, in order to relate the observed CMBR anisotropy to the structures that we see today (which are, in a sense, today's anisotropy), it is convenient to have measurements on smaller angular scales than COBE/DMR.

In anticipation of this need, GSFC started the MSAM project in 1988. Working at wavelengths between 0.5 and 3 mm, MSAM is a balloon-borne measurement of the CMBR anisotropy on angular scales between 0.5° and 3° . The experiment uses a 1-meter (m), off-axis telescope, coupled with a 4-spectral-band radiometer. The pointing for the experiment is controlled by a platform which was originally built in the early 1980s by a group at GSFC to map the Galactic plane. The payload is launched by the National Aeronautics and Space Administration's (NASA's) National Scientific Balloon Facility in Palestine, Texas, for overnight flights of 10 to 12 hours' duration. Approximately 6 to 8 hours of scientific data are returned for each flight, giving sufficient sensitivity to measure changes in the CMBR at the level of one part in 100,000. MSAM had its first flight in June 1992. This flight returned outstanding results, and detected anisotropy at the 3 parts per 100,000 level, which is consistent with reasonable theoretical extrapolations from the COBE measurements at larger angular scales. Detailed comparisons are in progress, but are inconvenienced by the extremely small signal levels and the small amount of data available. A second MSAM flight with the existing radiometer is planned for May 1994. Additional flights using a higher sensitivity, lower frequency radiometer are scheduled for May 1995.

In addition to the CMBR anisotropy, MSAM also detected two unexpected, unresolved (point-like), sources of radiation. If these are true CMBR signals, then the size distribution of the CMBR is dramatically different from that of the simplest theoretical predictions. If these sources are foreground astrophysical sources, then they may represent a new population of objects which could have far-

reaching impact on CMBR measurements at 0.5° angular scales. They could pose a serious astrophysical limit to the sensitivity which is achievable at certain measurement wavelengths. We are pursuing these unresolved source detections with ground-based measurements at different wavelengths.

The anisotropy detection by MSAM is at a level which is only a few times the minimum detectable level by the instrument. To provide higher reliability measurements, we have started a new project, TopHat, which will increase sensitivity by about a factor of 30. The concept is to place a receiver and a small (1 m) telescope on top of a balloon. With long-duration ballooning, which currently provides 2-week flights, such a configuration can provide an extremely stable, low-cost platform for CMBR anisotropy measurements. Placement on top of the balloon gives the telescope a completely unobstructed view of the sky. This top-mounted design may also prove to be a very cost-effective way to test hardware for future space missions. We have just begun the preliminary design and prototyping for this new experiment that is scheduled to fly in the 1996 time frame.

The study of CMBR anisotropy is still in its infancy, but has clearly entered a new phase. With the COBE/DMR discovery, the sensitivity level at which we need to work has been set. We have entered a measurement and characterization phase during which the smaller angular scales as probed by MSAM, TopHat, and future space missions will be key to uncovering the mystery of the origin of structure in the Universe.

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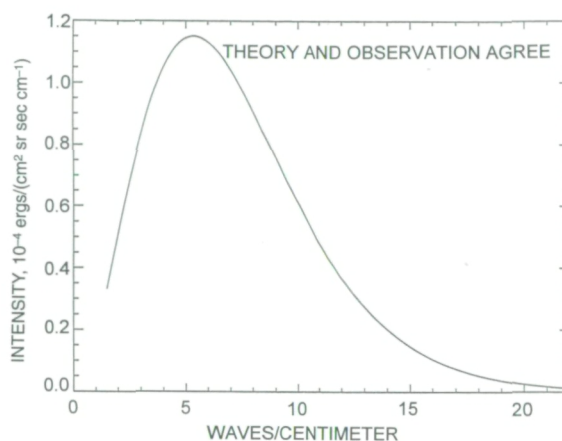


THE COSMIC BACKGROUND EXPLORER: MEASURING THE BIG BANG

THE BIG BANG, a theory which states that there was a cosmic explosion that began the expanding Universe 15 billion years ago, received its first experimental support in the late 1920s, when Hubble discovered the law that distant galaxies recede from us with speeds proportional to their distances. Modern distance measurements show that the explosion happened about 15 billion years ago. The theoretical basis was provided by Einstein's General Theory of Relativity, which shows that gravity acts by curving space and time and permits computations in an infinite Universe. In the 1940s, Alpher, Herman, and Gamow showed that the Big Bang idea predicts the existence of the CMBR, with a temperature a few degrees above absolute zero, and also predicts the correct relative abundances of the light elements hydrogen and helium. In 1964, Penzias and Wilson discovered the CMBR and began a new era of cosmology. In the 1980s, a new and radical idea became popular, that the properties of subatomic particles might actually be capable of causing an accelerating expansion in the Big Bang. This idea is called inflation for the initial period of exponential growth, like that seen in economics.

To acquire definitive data to address these ideas, COBE was launched on November 18, 1989, into a Sun-synchronous, circular polar orbit at a 900-km altitude, orbiting over the day/night boundary. The launch vehicle was a Delta rocket built by McDonnell Douglas, and the payload weighed 5,000 lbs. The COBE spacecraft and instruments were designed, built, and tested at NASA GSFC following project approval in 1982. More than 1,500 people worked to support the team of scientists.

In January 1993, the COBE team announced that they had tested the Big Bang theory to unprecedented accuracy. They showed that the spectrum of the CMBR has exactly the predicted shape, with an error of less than a part in 3,000 over the wavelength range from 0.5 to 5 mm (see first figure). They also measured the temperature, finding a value of 2.726 K. The implication is that the Big Bang was complete in the first instant, and less than a part in 3,000 of the energy in the CMBR was added to it after the Universe was 1 year old. Alternative explanations of the expanding Universe, such as the Steady-State theory and the Cold Big Bang theory, failed to predict the existence and spectrum of the CMBR correctly.



Far-Infrared Absolute Spectrophotometer (FIRAS) spectrum of the Big Bang, showing excellent agreement between prediction and measurement. The error bars are too small to plot.

The new limit on energy release after the Big Bang eliminates several popular theoretical speculations about its details. Cosmic strings had been suggested as explanations for the large-scale structure and the measured anisotropy. The strings are regions of space where the primordial material is preserved and which continue to release energy for a long time after the Big Bang. However, if they were abundant enough to explain the structure, they would have distorted the spectrum as well. In another speculation, there is strong evidence from optical and x-ray astronomy that there is invisible dark matter which makes up 90 to 99 percent of all the matter in the Universe. It had been suggested that some of this dark matter might decay, releasing electromagnetic energy long after the Big Bang, but the COBE results show that very little of this could have happened.

The new results also place strict limits on energy released in the formation of galaxies and clusters of galaxies. This process is still not understood, although COBE has provided the primary evidence of the initial conditions that caused this to happen. In 1992, the COBE team had already announced the discovery of the largest and oldest objects ever detected. As seen in the second figure, they are extremely faint ripples in the brightness of the CMBR, and the largest of them stretch across the whole sky. They show for the first time that the Big Bang was not per-

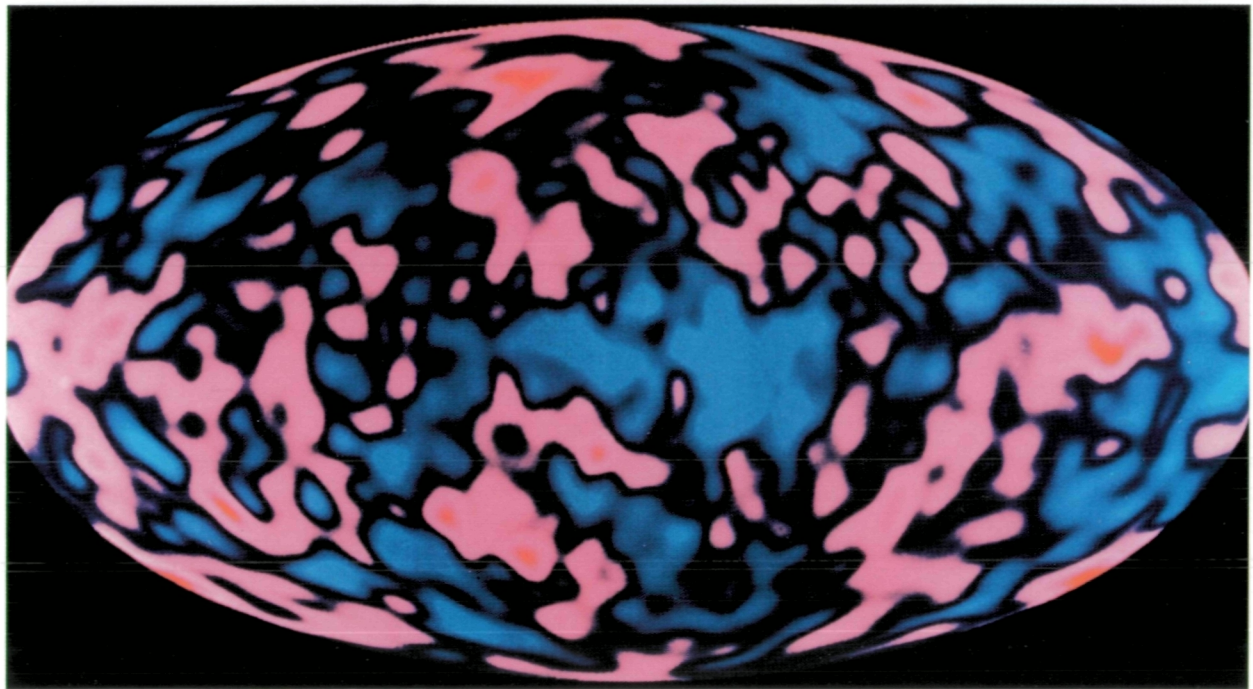
fectly smooth and uniform. Instead, there were regions of different temperature and density, having a wide range of sizes, which would eventually grow into the complex objects now seen by telescopes. The differences are very slight: only one part in 100,000 in temperature at the wavelengths measured by COBE: 3.3, 5.7, and 9.6 mm, with an angular resolution of 10° . Nevertheless, their discovery resolves one of the great mysteries of modern cosmology: what caused the Big Bang to break up into planets, stars, galaxies, and clusters of galaxies?

In 1993, the COBE team also announced that they had done additional tests of these small differences. They showed that there is no significant correlation between the bumps shown on the COBE sky maps with those found on any other likely source of diffuse microwave radiation. They compared their maps with maps of our own Galaxy made with radiation from hydrogen at 21-cm wavelength, with maps of the x-ray sky, and with maps of the locations and brightness of distant galaxies and clus-

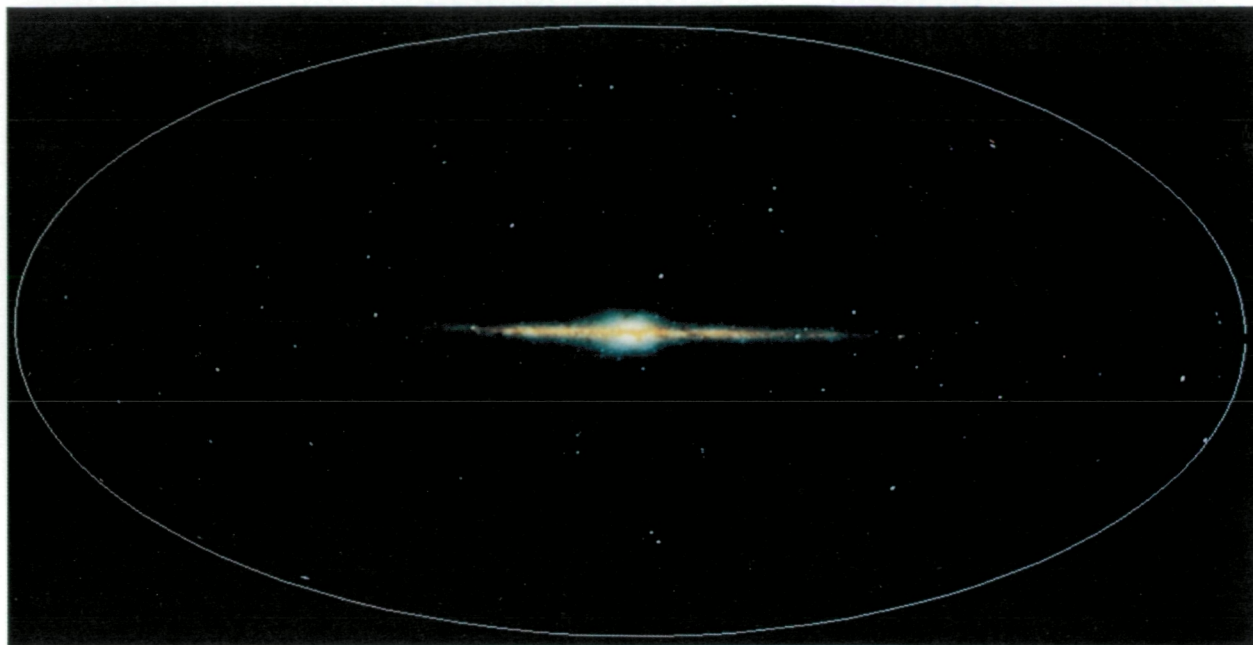
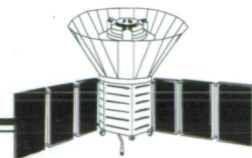
ters of galaxies. Thus, the maps really show features in the Big Bang itself.

COBE carries an instrument designed to detect the first light from the formation of galaxies or other objects after the Big Bang. It covers the entire infrared wavelength range from 1 to 300 μm with 16 detectors, and maps the entire sky (see third figure). Its beamwidth is much finer than the other two, only 0.7° . The interpretation of the data is difficult, because stars as well as dust grains in interstellar and interplanetary space all produce infrared radiation, too. However, if the analysis is successful, then we may discover a cosmic glow of first-generation stars and galaxies. This would be a truly remarkable finale for the trio of instruments aboard COBE.

The first datasets have been made public through the National Space Science Data Center (NSSDC) at GSFC, and a guest investigator program has begun for selected scientists to come to the Cosmology Data Analysis Center for assistance in working with the data. According to plan, the observations will continue until the end of 1993.



Differential Microwave Radiometer (DMR) map of the sky, showing hot and cold regions of the Big Bang itself. The emissions of the Milky Way have been subtracted.



Diffuse Infrared Background Experiment (DIRBE) image of the sky, including the Milky Way Galaxy and the central bulge of stars, at wavelengths of 1.2, 2.2, and 3.5 μm .

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Astrophysics Branch. He is interested in cosmology and infrared astronomy from space, and holds a BA in Physics from Swarthmore College and a PhD in Physics from the University of California at Berkeley. Recent awards include the American Institute of Aeronautics and Astronautics Space Science Award, the Aviation Week and Space Technology Laurels for Space/Missiles, and the Dannie Heineman Prize from the American Astronomical Society and the American Institute of Physics.

A COMPARISON OF THE COSMIC MICROWAVE AND COSMIC X-RAY BACK- GROUNDS: CONSTRAINTS ON LOCAL SOURCES OF THE FLUCTUATIONS OBSERVED BY COBE

COBE DMR measurements of small-scale, small-amplitude anisotropies in the microwave background are generally interpreted as the signature of density fluctuations in the Universe at the epoch of recombination. The result is of such significance to modern cosmology that it is important to examine carefully other plausible interpretations. One alternative explanation is that part of the fluctuations measured by the DMR are the signature of scattering by hot gas (the Sunyaev-Zeldovich effect; see below) which contributes to the Cosmic X-ray Background (CXB). This explanation has been tested by performing a cross-correlation of a 19-GHz survey of the microwave background with the High Energy Astrophysics Observatory-1 (HEAO-1) A2 all-sky survey of the 2- to 20-keV CXB. The lack of a detectable anti-correlation strongly limits the contribution of the Sunyaev-Zeldovich effect to the DMR fluctuations, and strengthens the interpretation that the fluctuations arose at the epoch of recombination.

Much care has been taken by the COBE team to ensure that the origin of the measured fluctuations are cosmic and not experimental. The possibility remains, however, that the fluctuations, while real, originate locally. In this context, local means beyond the Galaxy, but between the present and the epoch of recombination. Although its origin is not completely understood, there is general agreement that the CXB originates at redshifts between 0 and 5 and, therefore, meets the working definition of local.

The Sunyaev-Zeldovich effect is the scattering of microwave photons by electrons in gas with temperatures of several million degrees. The resulting microwave decrement has been observed behind a few bright, x-ray-emitting clusters of galaxies. The same gas which scatters the microwave photons is also responsible for the x-ray emission. If hot gas is sufficiently widespread, for instance, in superclusters of galaxies, to contribute significantly to the CXB, an anticorrelation between the microwave and x-ray backgrounds might be expected even if individual features are too weak to be individually identified.

The size of the microwave background fluctuations expected from such a source depends on the typical parameters of the hot gas clouds and scale roughly as the product of the size, density, and temperature. The x-ray emission from the same cloud is proportional to the product of size,

the square of the density, and the square root of temperature. The cross-correlation function, which can be measured for any angular separation, therefore depends on the product of the square of the size, the cube of the density, the $3/2$ power of the temperature, and a dimensionless parameter which is a function of angular separation, and depends on the density and distribution of gas clouds. Even if the gas clouds are assumed to have characteristics consistent with superclusters, none of these parameters are well-known. However, the auto-correlation of the microwave background depends on the product of square of the size, the square of the density, the square of the temperature, and the same dimensionless parameter. Therefore, the ratio of cross-correlation of the two surveys to the auto-correlation of the microwave survey depends only on the product of density and the square root of gas temperature, and exhibits a much smaller dependence on the model parameters—density, and temperature.

The cross-correlation analysis has been conducted with a balloon-borne 19-GHz survey and the HEAO-1 A2 all-sky survey. The 19-GHz signal is probably dominated by radiation with the same origin as in the DMR bands; indeed, the 19-GHz instrument was considered as a potential part of the DMR experiment. The GSFC HEAO-1 A2 experiment, launched in 1977, remains the most sensitive x-ray all-sky survey in the 2- to 20-keV band. The lack of anticorrelation has been independently confirmed by comparing the A2 map with the DMR data.

The ratio described above leads to conclusions about allowed combinations of density and temperature. Assuming that characteristic sizes of supercluster gas clouds are less than 100 megaparsecs (about the largest size of any known density perturbations) requires that the gas temperature be less than 0.35 keV or greater than 16 keV (a parsec, or parallax-second, is about 3.26 light-years). The lower temperatures are disallowed by observations of the CXB at ~ 0.25 keV. The higher temperatures are ruled out by the lack of spectral distortion in the COBE spectrum of the microwave background. The DMR fluctuations, therefore, are unlikely to be caused by x-ray emitting gas, and the Sunyaev-Zeldovich effect is therefore unlikely to be a significant contributor to these fluctuations. This work was performed in collaboration with Stephen Boughn (Haverford College). The independent confirmation com-



paring the A2 map and the DMR data was performed by Charles Bennett (GSFC) and collaborators.

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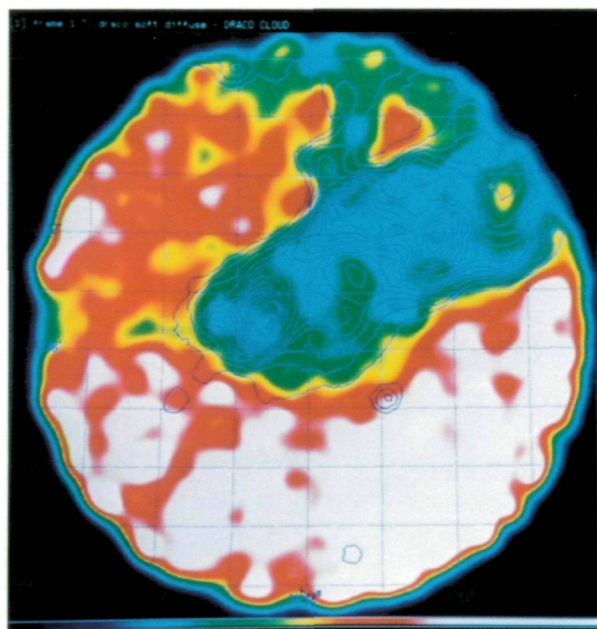
HIGH ENERGY

THE X-RAY SKY AS REVEALED BY ROSAT

OVER ITS 3 YEARS of operation, the Röntgen Satellite (ROSAT) has provided the most revealing picture of the x-ray sky ever obtained. Its all-sky survey, complemented by deep pointings, has provided new insights into the physics of the Universe.

ROSAT is a joint German/U.S./U.K. mission. Its scientific instrumentation consists of a high-resolution x-ray telescope and a focal plane carousel containing two different x-ray imaging cameras. The x-ray telescope is the finest ever flown, and has a spatial resolution of 2 arcsec. In the focal plane are the German-built Position-Sensitive Proportional Camera (PSPC) and the U.S.-supplied High Resolution Imager (HRI). The PSPC offers near-unit quantum efficiency over most of the 0.1- to 2.4-keV (5 to 100 Å) band, and spectral resolution capable of resolving four distinct colors. Its low intrinsic background, coupled with the large mirror collecting area, makes it the most sensitive x-ray detector ever placed into orbit. The PSPC has a spatial resolution of about 20 arcsec. The HRI samples only the central 40 arc minutes (arcmin) of the field of view. While it has essentially no spectral resolving power and a quantum efficiency of ~30 percent, its spatial resolution is limited only by the telescope. Thus, the HRI offers the highest resolution view of cosmic x-ray sources ever attained.

ROSAT was launched from the Kennedy Space Center (KSC) on June 1, 1990. After a 2-month performance verification phase, it spent 6 months scanning the entire sky, and then focused on specific objects. One of the very first pointed observations yielded the discovery of the first x-ray shadow. The existence of an all-pervasive x-ray background has been known since the inception of x-ray astronomy in 1962. While at energies above the ROSAT bandpass, this background is clearly dominated by extragalactic emission, the ROSAT band background has a substantial contribution from within the Galaxy. The primary source of the soft Galactic x-ray background has been thought to be hot (2×10^6 K) gas filling a large cavity, of extent ~200 pc, in which the Sun is embedded. A determination of the extent of this cavity and the distribution of hot gas within it was thought to be possible by measuring the reduction of x-ray surface brightness in the direction of diffuse clouds within it. As shown in the first figure, the contours of x-ray surface brightness anticorrelates with those of emission at 100 μ m, which



The first x-ray shadow. Colors represent the intensity of 0.1- to 0.3-keV x-rays; contours represent the 100- μ m surface brightness associated with hot dust in the x-ray absorbing cloud.

reveals the warm dust associated with the cloud. What was astonishing about the result is that the cloud responsible for the shadowing is at a distance of 500 pc, well beyond the supposed edge of the local cavity. Moreover, as the cloud is at a high galactic latitude, the presence of the shadow reveals the first definitive evidence of a massive halo associated with the Milky Way Galaxy. Detection of other shadows from more nearby clouds is leading to both a quantification of the mass of the halo and a refinement of our knowledge of the distribution of diffuse matter in the solar neighborhood.

ROSAT's ability to observe fainter x-ray sources than any previous x-ray observatory has also been utilized to study the composition of the extragalactic x-ray background. By pointing in a single direction for ~50,000 s, ROSAT has directly resolved into discrete sources approximately 50 percent of the flux in the 1- to 2-keV band. Comparison of these sources with optical images and spectra help reveal their nature. Many of these sources are active galactic nu-



clei; others appear as otherwise-normal galaxies that are for some unexplained reason, extremely x-ray luminous. Still other sources have no observed or classifiable counterpart. The integrated spectrum of the resolved sources and that of the residual unresolved emission is very similar, indicating that this flux arises in similar sources too weak to be detected individually by ROSAT.

ROSAT has observed a number of recent supernovae in other galaxies. The best known of these was ROSAT's detection of the Type II supernova SN1993J, in the nearby spiral Galaxy M81. ROSAT observed the supernova 5 days after it had attained its optical maximum, the earliest any such x-ray observation had occurred. Observations over the subsequent 1.5 months showed the x-ray luminosity to decrease much more slowly than predicted by any theoretical model. The x rays are produced when the energetic blast wave from the supernova encounters and heats circumstellar gas that had been slowly ejected from the progenitor star over thousands of years in the form of a wind. The variation in the x-ray luminosity and temperature will allow a measurement of the density profile of the wind material and thus trace the history of the mass loss by the progenitor. A similar set of measurements is being performed on two other supernovae. SN1986J and SN1978K in the nearby spiral galaxies NGC 891 and NGC 1313 were detected by ROSAT with a luminosity 10 times that of SN1993J, 7 and 13 years after their explosions. These stars have extremely massive circumstellar disks, and much of the 10^{51} ergs of kinetic energy released by the explosion is converted to thermal energy as the shock propagates through the massive, dense envelope. SN1978K was the first supernova to be identified as such based on its x-ray emission.

For nearly 2 decades, one of the most challenging enigmas in high-energy astrophysics has been to determine the nature of a γ -ray source known as Geminga. This is one of the brightest γ -ray sources in the sky, yet there was no strong optical candidate. Pre-ROSAT x-ray observations showed Geminga as a modest x-ray source, but offered no other evidence about its nature. A ROSAT observation revealed that Geminga pulses with a period of 0.247 s, ruling out any interpretation other than a neutron star. Its x-ray spectrum has two components; one with a temperature of 300,000 K, originating from the neutron star surface, and a second, much hotter, strongly pulsed component, thought to be associated with the magnetic-field poles where particle acceleration and γ -ray production occur.

Clusters of galaxies are the largest self-gravitating structures in the Universe. Previous x-ray observations had revealed substantial amounts of hot gas trapped within the gravitational well of these clusters. As this gas is, for the most part, in hydrostatic equilibrium (unlike the individual galaxies), measuring its temperature and density profile using x-ray detectors is the most reliable means of measuring the mass of clusters. Imaging observations using ROSAT's predecessor, the Einstein Observatory, had suggested that most clusters are spherically symmetric, gravitationally relaxed structures. ROSAT, with its higher spatial resolution and sensitivity to surface brightness variations, has revealed quite a different picture. A large number of clusters, even very old ones which presumably have had time to reach an equilibrium, show structure, in the form of subclusters of galaxies. This structure is taken as evidence that in general, clusters grow by agglomerating subclusters, and that this process is ongoing. There seems to be no correlation of degree of structure with cluster age: some rather nearby (and thus old) clusters are still in the process of congealing. Rather, the process seems most dependent on the size of the primordial density perturbation responsible for the initial formation of a cluster.

One of the most far-reaching discoveries using ROSAT is that much of the mass in the Universe might not be in clusters. For years, cosmologists have wrestled with the observational fact that the observable matter in the Universe constitutes only a small fraction of that which is needed to close it. This is known in the literature as the missing mass problem. While some amount of "dark matter" is required to supply the gravitational force holding clusters of galaxies together, the amount of such material is insufficient to close the Universe. A ROSAT observation of a poor group of galaxies, a group of only two galaxies held together gravitationally, revealed a massive halo engulfing the galaxies, as shown in the second figure. A calculation of the amount of dark matter required to gravitationally confine the halo yielded the first-ever observational evidence for a sufficient quantity of dark matter to close the Universe. This landmark result has now confirmed at least one similar group.

While these discoveries are among the most important reported in the more than 150 ROSAT papers that have already appeared in refereed publications, there is an enormous archive of ROSAT data from which even more important discoveries could easily be made. Moreover, ROSAT continues to carry out its mission, observing



The distribution of diffuse hot gas in the NGC 2300 group of galaxies overlaid on an optical plate. This observation offers the first hard evidence for dark matter with density sufficient to close the Universe.

approximately 20 additional x-ray sources every week. A great deal more about the x-ray sky will be revealed by ROSAT before its work is done.

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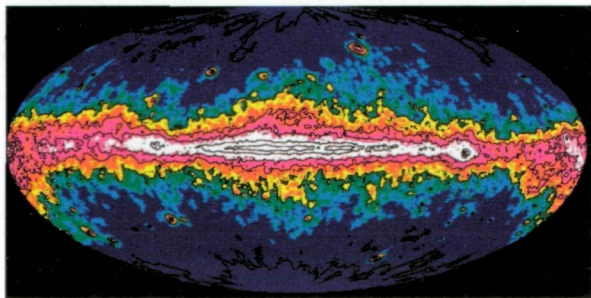
Dr. Robert Petre is the U.S. ROSAT Project Scientist. Dr. Petre earned his PhD in Physics from MIT in 1982. He has been at GSFC since 1985, as an astrophysicist in the X-ray Astrophysics Branch of the Laboratory for High Energy Astrophysics. He has served as Experiment Scientist for the Broad-Band X-Ray Telescope, is a member of the Advanced Satellite for Cosmology and Astrophysics science team, and has been involved with ROSAT since 1985. His research interests focus on x-ray emission from supernovae and supernova remnants, normal and active galaxies, and white dwarf stars.



DIFFUSE GAMMA-RAY EMISSION IN THE GALAXY

WHEN THE SKY is viewed at gamma-ray energies, an intense ridge of emission is seen for a latitude region of about 10° from the galactic plane. It is especially intense for longitudes that are within 60° of the Galactic Center. The first figure shows the gamma ray intensity above 100 MeV made by the Energetic Gamma-Ray Experiment Telescope (EGRET) instrument on the Compton Gamma Ray Observatory (CGRO) during the all-sky survey in Phase 1 of the mission. Most of the emission seen here is the by-product of cosmic-ray interactions with interstellar gas and low-energy photons; as a result, its spatial distribution is extended or diffused rather than originating from localized point sources. The principal production mechanisms are nuclear interactions that yield gamma rays through secondary pi-meson decay, electron bremsstrahlung, and inverse Compton interactions between electrons and low-energy photons. Nuclear interactions dominate above 100 MeV, and bremsstrahlung is most significant below about 60 MeV.

The spatial and energy distribution of the diffuse gamma-ray emission observed by EGRET, together with recent surveys of matter distributions made with radio surveys, offer new information on how cosmic rays are distributed and confined in the Galaxy, and indirectly on the role of cosmic rays in the dynamical relationship between matter, magnetic fields, and cosmic rays. However, the galactic diffuse gamma emission also presents a high background for observations of sources near the Galactic plane. This especially affects the study of Galactic point sources such as pulsars. Consequently, it is important for



Galactic map of gamma-ray emission above 100 MeV observed by the EGRET instrument during the all-sky survey. The high intensity in the Galactic plane is evident based on the intensity of the red and white bands in the central region of the plane.

EGRET data analysis to have a tool that accurately predicts the diffuse emission, and further, that the model is structured to facilitate physical interpretation when data from the full-sky survey are fully processed and are compared to calculated values.

We have developed a model of the Galactic diffuse emission specifically to aid in the analysis and interpretation of the EGRET γ -ray observations. Diffuse gas, cosmic rays, and photon energy densities were determined from the best recent data in a 3-dimensional grid with 0.5° in Galactic longitude and latitude and 0.5 kpc in line-of-sight distance for the Galaxy out to a radius of 20 kpc. Well-known production cross-sections were then used to compute the gamma-ray production as a function of energy from each cell of the grid, and line-of-sight integrations were performed to predict the observed diffuse emission intensity as a function of energy and direction. This approach differs from most past efforts in several ways. First, it was possible to establish the gas distribution without assuming azimuthal symmetry in the Galaxy. Most models in the past have invoked axial symmetry that can mask important distinctions from spiral arm features that potentially may be detected in the data. The model incorporates new data on the distribution of gas and low-energy photons. An effort was made to keep the number of free parameters to a minimum to maximize its utility for understanding the implications of the EGRET diffuse data. Only two free parameters were used: the global ratio between the molecular hydrogen density and the observed line emission of the CO molecule, and the coupling scale length over which the matter density is averaged to define the cosmic-ray density.

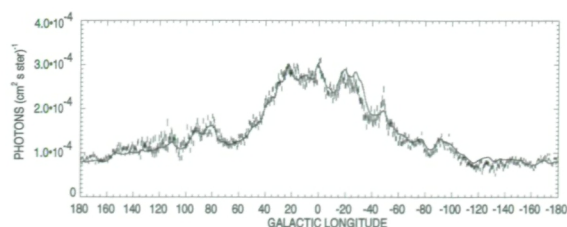
Available radio survey data for atomic hydrogen give the intensity of the 21-cm line emission as a function of the recession velocity. A Galactic rotation curve model that relates rotation velocity to distance from the Galactic Center was used to deconvolve the recession velocity to yield a distance from Earth. Molecular hydrogen cannot be observed directly, but instead radio survey data of CO, which is thought to be a good tracer gas, was used, and a conversion to molecular hydrogen was introduced as one of the parameters of the model. This ratio, usually called the X-factor, is in the range of $X = N(\text{H}_2)/W_{\text{CO}} = (1 \text{ to } 4) \times 10^{20} \text{ molecules/cm}^2/(\text{K km/s})$. Ionized hydrogen was also included, based on a distribution model that was developed

to account for radio pulsar dispersion measures. The gaseous matter for nuclei heavier than hydrogen is expected to add another 10 percent, and this adjustment was made.

The interstellar photon density distributions that are of interest in calculating the inverse Compton contribution are primarily those from the cosmic microwave background and the infrared, optical, and ultraviolet wavelength regions. The microwave radiation is uniformly distributed. The position distributions of the other three spectral regions were modeled in four wavelength regions between 8 and 1,000- μm based on analysis by other workers.

The spatial distribution of cosmic rays in the Galaxy is not known, but arguments based on the balance between the gravitational attraction and the expansive cosmic-ray and magnetic pressures lead to the assumption that the cosmic-ray density is coupled to the matter density, smoothed over some characteristic length. This assumption is made in the model where the characteristic, or coupling, length is included as a free parameter to be determined by the best fit to the gamma-ray data. The range in coupling lengths is thought to be greater than 0.5 kpc, since the scale height of cosmic rays normal to the plane is probably greater than 1.0 kpc. The coupling length is likely to be less than 6.0 kpc, otherwise cosmic rays would not be correlated with matter, but would be uniformly distributed through the Galaxy.

The second figure shows a comparison between the model prediction for diffuse gamma-ray emission at energies above 100 MeV summed over Galactic latitudes from -10° to 10° as a function of Galactic longitude. The predicted intensities have been folded with the EGRET instrument angular response function to facilitate comparison between the prediction and the data and are shown by the solid curve. The data points in the second figure are the EGRET observations of emission in the same latitude band. The point sources detected by EGRET have been subtracted. In this analysis, the values of the two free parameters have been set to $X = 2.0 \times 10^{20}$ molecules/cm 2 /(K km/s) for the factor relating CO to molecular hydrogen, and 2.0 kpc for the cosmic-ray coupling scale. Both values are well within the expected ranges. No detailed attempt has been made to optimize the parameters, but X cannot differ by more than ~ 40 percent from the selected value, and the coupling scale cannot be so large that the cosmic rays are effectively uncoupled with matter. These extremes have been tested and ruled out.



The Galactic longitude distribution of gamma-ray intensity summed over the latitude range from -10° to 10° for gamma-ray energies above 100 MeV. The solid curve is the diffuse emission predicted by the model and convolved with the EGRET point-spread function. The vertical bars represent EGRET observations summed for all viewing periods in the all-sky survey.

The agreement between the model prediction and the data is striking in that both the broad features and small-scale structures agree. Minor disagreements are noted in the region around -20° to -35° and perhaps around -120° . Further work is in progress to explore these apparent differences. They may be traceable to the Galactic rotation curve, or additional matter may be present, possibly from a localized enhancement of the X-factor or from some additional matter, or unresolved sources may be present. If any of these explanations prove to be likely, important new information on the Galaxy will be gained. Similar good agreement is found when latitude profiles are made at different longitudes.

Some analysis has been done on the energy spectrum of the diffuse emission, especially near the Galactic Center and anticenter, and again, the model values agree very well with the observation. Further work on these studies is in progress.

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Dr. David Bertsch works in the Laboratory for High Energy Astrophysics and has been at GSFC for 25 years. He received his PhD in Physics from Washington University. He is a Co-Investigator on the EGRET instrument on CGRO, and participated in its hardware and software development. He is an Assistant Project Scientist for CGRO and is Chairman of its Timeline Committee. He received several Group Achievement Awards for GRO and was co-recipient of the 1993 Lindsay Award for Scientific Achievement.



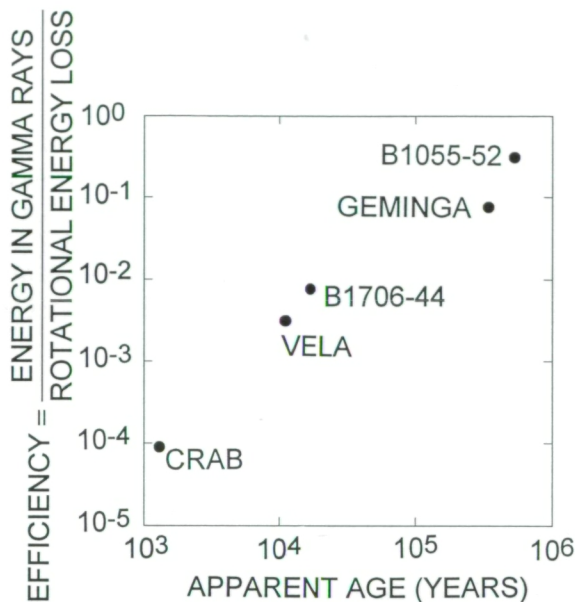
GAMMA-RAY PULSARS: EFFICIENCY INCREASES WITH AGE

PULSARS, THE RAPIDLY spinning stellar cores left behind by supernovae, are usually observed by radio telescopes. Five of these pulsars have now been observed by EGRET on the CGRO. In all cases, the high-energy gamma rays represent far more energy from the pulsar than the radio waves. In the most recent discovery, Pulsar B1055-52 is seen to convert over 10 percent of its total energy budget into gamma rays. This finding confirms a trend which was noticed and modeled over 10 years ago: older pulsars appear to be far more efficient producers of gamma rays than are younger pulsars, as shown in the figure. This pattern can be explained as either an increase in the flow of high-energy particles (which produce the gamma rays) or an enlargement of the region which boosts the particles to higher energies. In either model, additional gamma-ray pulsars would be expected, and recent EGRET results show that some of these are not seen at the expected intensity. These new results indicate that more complex models may be required to explain the gamma-ray pulsar phenomena.

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For the five pulsars detected by EGRET, the efficiency for conversion of the pulsar's spin energy into high-energy gamma rays is larger for older pulsars.

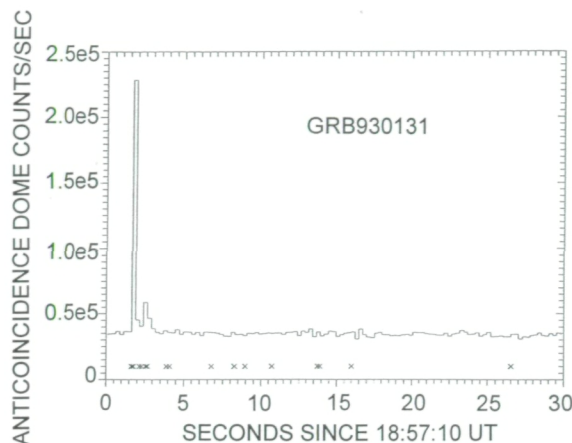
THE ENERGETIC GAMMA-RAY EXPERIMENT TELESCOPE OBSERVES THE HIGHEST ENERGY EMISSION FROM GAMMA-RAY BURSTS

EGRET IS AN INSTRUMENT on the CGRO. It has observed the highest energy emission ever seen from many types of astrophysical sources. CGRO was launched on April 5, 1991; since that time, EGRET has detected high-energy gamma rays from objects as disparate as active galactic nuclei at distances of billions of light-years, to pulsars within our own Galaxy at distances of thousands of light-years, to our own Sun. Prior to the launch of EGRET, most of these objects were not known to emit such high-energy gamma rays. Similarly, gamma-ray bursts have been observed by EGRET at energies an order of magnitude higher than previously known.

Gamma-ray bursts are flashes of electromagnetic energy which occur about once per day and last anywhere from a fraction of a second to minutes. These flashes are equally likely to come from any direction, and only gamma rays are observed; no counterpart has been seen in any other range of the electromagnetic spectrum. The lack of information from other wavelengths, and the absence of lines in most of the gamma-ray burst energy spectra make it difficult to determine much about the origin of these bursts. Indeed, we still do not know whether they originate within or outside our Galaxy.

On January 31, 1993, a very intense gamma-ray burst was observed by CGRO. The figure shows how the intensity of gamma rays varied with time. The shape of this curve is similar to other gamma-ray bursts, yet the peak intensity is much greater, and the energy of the highest energy gamma rays is much higher: EGRET detected gamma rays of energy ten times higher than ever observed before in a gamma-ray burst. The highest energy photons were 1 GeV, and the spectrum is fit by a single power law from 1 MeV to 1 GeV, which indicates that equal power is observed in each decade of energy.

The highest energy photons provide important clues about the source of gamma-ray bursts. The observed extension of the energy spectrum to higher energies rules out thermal radiation from most sources. One possible origin theory would create gamma rays from charged particles which can be accelerated by shocks. However, creating the gamma rays is not the most difficult problem faced by the theories, because the highest energy gamma rays are easily destroyed at the source by interactions with more plentiful lower energy gamma rays. These interactions can be prevented if gamma rays are emitted from material



Light curve of the January 31, 1993 gamma-ray burst; the crosses indicate the arrival times of the gamma rays above 30 MeV.

moving very close to the speed of light. This could result in a narrow beam of almost parallel gamma rays. To observe such a small beam, that beam must be pointed towards the observer. It is unlikely that such beams would be preferentially pointed towards the Earth, so there may be many more objects emitting gamma-ray bursts that we do not see because their beams are pointed elsewhere.

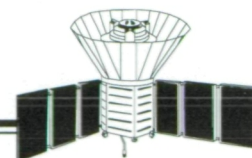
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Dr. Carl Fichtel is Chief Scientist in the Laboratory for High Energy Astrophysics, Acting Head of the Gamma-Ray Astrophysics Branch, and a Goddard Senior Fellow. Among other awards, he has received the John C. Lindsay Memorial Award and the NASA Exceptional Scientific Achievement Medal. He holds a PhD from Washington University in St. Louis.

Dr. Brenda Dingus came to GSFC 4 years ago. She is now a research scientist with the Universities Space Research Association (USRA) and a member of the EGRET scientific team. Her research interests include gamma-ray bursts as well as detector development. She holds a PhD from the University of Maryland and a BS from Harvey Mudd College.



TOWARDS RESOLVING THE GAMMA-RAY BURST MYSTERY

A QUARTER of a century has elapsed since the discovery of cosmic gamma-ray bursts by the Vela satellites. Hundreds of these brief flashes of intense gamma radiation have been observed, but neither a source identification nor an understanding of the burst process has been achieved. Networks of burst experiments established in the inner Solar System since 1976 have made source location studies using the method of arrival timing analysis, but after-the-fact searches of the arc-minute-sized celestial fields have shown no pattern of counterparts at any other wavelength.

A new and dramatic project in CGRO data analysis takes advantage of the real-time data acquisition (necessary after the CGRO tape recorders failed) to provide burst source directions on a near-real-time basis for use by other telescopes. Using observations from the eight large detector modules of the Burst and Transient Source Experiment (BATSE), calculations at the GSFC control center compare the intensities—as the raw data are received—to estimate the burst source direction with an accuracy limited to several degrees by systematics. Real-time computation of burst positions is now operational, and the output is available to the scientific community within seconds of the onset of each burst, often while the event is still in progress.

One of the intended applications of this scheme is to provide a second-stage process of real-time localization which will reduce the error from degrees to arc minutes. A dedicated telephone line will send the coordinates of the coarse gamma-ray burst localization to the Goddard Geophysical and Astronomical Observatory (GGAO). The coordinates are received at the 48-in telescope, which has a camera with a 4-in-diameter objective lens mounted piggyback on the scope observing platform. The telephone signal is received by a dedicated personal computer and can be transmitted automatically to the scope tracking and control computer, where it is processed. The dome and scope/camera configuration slew at 6° per second, accessing all parts of the sky within half a minute. A large fraction of bursts would still be in progress at gamma-ray energies. Because bursts often last longer at x-ray energies, it is conceivable that many bursts might persist even longer at optical wavelengths. The camera field of view can zoom down from a maximum of 20° , sufficiently large to accommodate error regions derived in the first stage of

localization. The burst field is viewed by a 1-in format silicon-intensified-target video camera whose output is recorded continuously on video tape. Eighth to ninth magnitude point-like objects are observable with the current configuration, and 12th magnitude could be reached with available intensifiers. The video format is potentially analyzable in real time using a frame grabber, and automated comparisons with catalogued objects would reveal the presence of any transient image. This information would be transmitted to the Rapidly Moving Telescope (RMT) on Kitt Peak, an operational system with arcsec imaging capability. The entire train of events from burst onset to third stage of localization should be accomplished in less than 1 minute. A significant improvement in response speed can be realized by utilizing a two-axis, gimballed, instantaneous-slew optical flat (similar to that in the present RMT), viewed by an optical system with a field of view comparable to the current second-stage camera. This siderostat arrangement is currently being upgraded at the GGAO.

The default consensus of the 1980s was that gamma-ray bursters must be dead neutron stars, with an expected source-clustering along the galactic plane that would be revealed with sufficiently sensitive detectors. BATSE has not confirmed the galactic disk hypothesis—the celestial distribution of 750 BATSE burst localizations is essentially isotropic—but instead has provided impetus to a new rush of theories, including some which place the burst sources at cosmological distances. No significant dipole or quadrupole moment in the source distribution is found with reference to any coordinate system, including metagalactic ones. BATSE has the sensitivity to detect very weak bursts, but not enough are seen relative to the number of more intense bursts. This result implies that CGRO has seen an edge to the burst spatial distribution. Combined, isotropy and the source volume limit indicate that bursts originate in a spherical source distribution—either near the heliosphere in an unexpectedly large halo around our Galaxy, or at cosmological distances. With the distance scale to gamma-ray bursters virtually unconstrained, their power output and primal energy source are entirely open to speculation. If the sources are near the heliosphere, then gamma-ray bursts are puny compared to x-ray bursts or pulsars. If cosmological, then the powerhouse is enormous, even up to one quintillion (10^{18}) suns, during the very brief explosions.

Several new approaches to the analysis and interpretation of BATSE data have been designed to test the cosmological hypothesis. The spectra of the weaker, less numerous bursts should appear redshifted below about 100 keV, where spectral curvature is manifest. Attendant with redshift is time dilation: time intervals from more distant bursts should be stretched as the events make their way across the expanse of space. The time dilation factor is $(1+Z)$, where Z is the redshift. We selected 135 bright and dim gamma-ray bursts detected by BATSE and performed a procedure to render uniform the burst signals, backgrounds and noise biases, virtually eliminating brightness selection effects. Multiresolution temporal analysis techniques—a wavelet spectrum test and a peak alignment test—indicate that a stretch ratio of approximately two is manifest (dim bursts are longer) over each of seven octaves in width of temporal structure (0.5 to 65 s), as required to be consistent with cosmological time dilation. The efficacy of these tests is that they segregate (wavelet spectrum) or order (peak alignment) the information by width of temporal structure, and thereby tend to address the dispersion of widths of features in burst temporal profiles. The stretch factor of two translates into a redshift of unity for the dim bursts. The average spectral hardness ratio for the dim bursts is much softer than that for the bright bursts; this may be the expected spectral redshift effect. We have also modeled the number versus intensity relation—the indicator that weak bursts are undernumerous—and found $Z \sim 1$ for the dim bursts. Finally, if the dim bursts came from sources at redshifts much greater than unity, then an example of gravitational lensing by an intervening galaxy should have been found by now. The expected signature for a galactic-sized lens would be two or more images of the same burst, separated in time by hours to years, with only intensity rescaled; spectral and temporal variations are invariant. A comprehensive search for lensed bursts has been undertaken, examining 1700 pairs with mutually consistent

localizations, and no candidate has been found, as expected for $Z \sim 1$. Thus, the number-intensity relation, the apparent time dilation effect, and lack of a gravitational lens candidate are all consistent with a redshift of $Z \sim 1$.

The successes of the BATSE experiment are a tribute to the efforts of the Principal Investigator Team, led by Dr. Gerald Fishman at NASA Marshall Space Flight Center. At NASA Goddard, the cosmological studies have been done by Drs. J. P. Norris and R. J. Nemiroff. Drs. S. Barthelmy and T. L. Cline have led the effort to produce real-time BATSE burst analysis; Drs. J. Bonnell, Norris, and the Laser Ranging and Altimetry Group are among those collaborating on the second-stage implementation of the gamma-ray burst rapid response capability.

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Dr. Jay P. Norris is Deputy Project Scientist for the Compton Gamma Ray Observatory. His University of Maryland PhD dissertation was on gamma-ray bursts using GSFC observations from the ISEE-3 and the Solar Maximum Mission spacecraft. Following further work at the Naval Research Laboratory, he returned to Goddard's Laboratory for High Energy Astrophysics, where his current research focuses on searches for cosmological signatures in gamma-ray bursts.

Dr. Thomas L. Cline is Senior Scientist and Head of the Nuclear Astrophysics Branch in Goddard's Laboratory for High Energy Astrophysics. He received his PhD from MIT. Upon the discovery of gamma-ray bursts, he flew the first instruments intended for their study and created the interplanetary gamma-ray burst networks.



ADVANCED SATELLITE FOR COSMOLOGY AND ASTROPHYSICS SUCCESSFULLY LAUNCHED AND RETURNING RESULTS

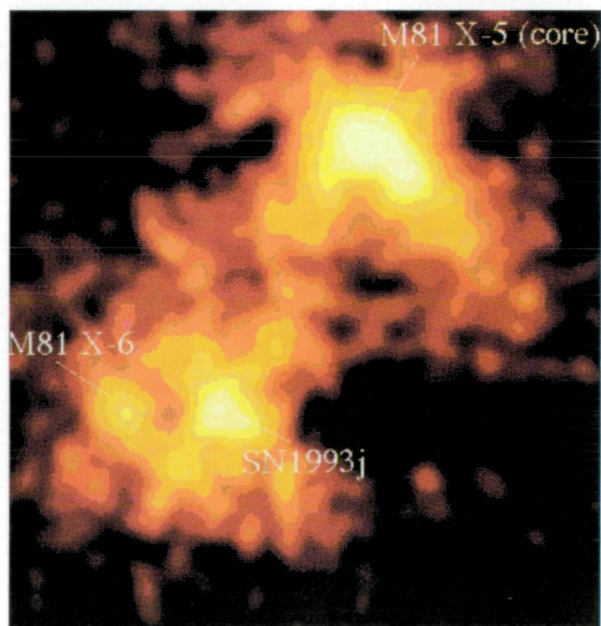
JAPAN'S FOURTH X-RAY astronomy mission (Astro-D) was successfully launched on February 20, 1993, at 11:00 JST (02:00 UT) from Kagoshima Space Center. After launch, the satellite was renamed Advanced Satellite for Cosmology and Astrophysics (ASCA) (the Japanese characters mean a flying bird). ASCA is a cooperative venture between NASA and Japan's Institute of Space and Astronautical Science (ISAS). NASA's contribution includes four conical, grazing-incidence, thin-foil mirror assemblies, two charge-coupled devices (CCDs), and data analysis software. Japan has provided the spacecraft, two gas-imaging scintillation counters, the launch, and overall program management. In return for its contribution, the U.S. receives 15 percent of the observing time, with an additional 25 percent for collaborative U.S./Japan investigations. The first 8 months of the mission were reserved for instrument checkout and performance verification. Following this, the U.S. share of the observing time is open to all astronomers affiliated with a U.S. institution.

The main science objective of ASCA is x-ray spectroscopy, with particular emphasis on the iron K line around 6 keV (1 angstrom ($\text{\AA}$)). The lightweight foil telescopes were developed at GSFC by Peter Serlemitsos from the X-Ray Branch of the Laboratory for High Energy Astrophysics (LHEA). This pioneering technology allows a large, broadband collecting area with an angular resolution on the order of 1 arcmin to be flown. The first flight of this mirror design was as the Broad-Band X-ray Telescope (BBXRT) on the Space Shuttle *Columbia* (STS-35) in December 1990, with a solid-state spectrometer at the focus. The brief glimpse of the sky afforded by this mission demonstrated the power of studying the entire 1- to 10-keV x-ray band with an imaging telescope. On ASCA, the CCD spectrometers, provided by the Massachusetts Institute of Technology (MIT), give a resolution of ~ 2 percent at 6 keV. This resolution will provide new, detailed x-ray spectroscopy of virtually every class of astronomical object including stellar coronae, x-ray binaries, active galactic nuclei, supernova remnants, clusters of galaxies, and cataclysmic variables.

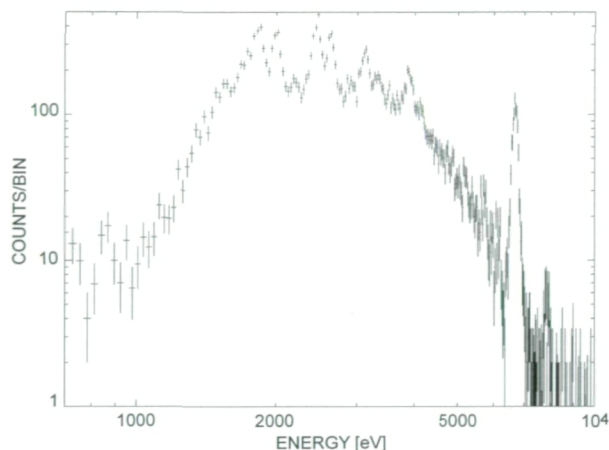
ASCA has an orbital period of 96.09 min, an orbital inclination of 31.10° , a perigee of 523.6 km, and an apogee of 615.3 km. The orbital lifetime is expected to be on the order of 10 years. First light was on March 17, 1993, when

the x-ray binary EXO0748-676 was observed. The instrument turn-on and checkout phase went as expected, and ended on April 19, when the 6-month performance verification observation phase began. The ASCA instrumentation has continued to work within specification, and the overall goals of the mission are being met. Samples of all important classes of astrophysics objects have now been observed, and many more observations are planned.

Fortuitously, 1 month after the launch of ASCA on March 26, 1993, the brightest supernova in the northern skies in more than 50 years was discovered in the nearby spiral Galaxy M81, located in the constellation Ursa Major. This type II supernova, designated SN1993J, is thought to result from the final collapse of the iron core of a star 10 to 20 times more massive than the Sun. ASCA observed SN1993J as a target of opportunity on April 5, 5 days after maximum optical light. The image taken using the CCD detectors is shown in the first figure. A new x-ray source was detected by ASCA 3 arcmin from the previously known x-ray source (X-5) at the core of M81, and



An x-ray CCD image of the Galaxy M81 taken by ASCA in April 1993. The supernova, SN1993J, is indicated. It lies about 3 arcmin from the x-ray emitting core of the Galaxy (X-6).



An ASCA CCD spectrum of the supernova remnant W49B reveals the presence of many strong emission lines, and demonstrates the power of this instrumentation.

coincident with the position of SN1993J. The x-ray luminosity was equivalent to 2 million times that of our Sun and about 0.1 percent of the total output from the supernova. ASCA continued to monitor the supernova and found the x-ray flux to decline with an exponential folding time of 55 days. The x-ray spectrum shows a strong iron emission line, indicative of thermal emission. The x-rays detected come from shock-heated material from the progenitor's outer envelope.

Supernova explosions such as SN1993J eject debris and shock fronts that interact with the interstellar medium. The supernova remnant will, with a few tens of years,

become a bright x-ray source as the shock front expands outward. These x-ray sources are rich in emission lines, which ASCA is particularly well-suited to study.

Another example of the outstanding results being obtained by the CCD instrumentation is shown in the second figure, which is a spectrum of the supernova W49B. This remnant is located in our Galaxy at a distance of 10 kpc, and is the remains of a supernova explosion that occurred about 6,000 years ago. The ASCA spectrum shows strong emission lines from silicon (1.8 and 2.0 keV), sulphur (2.4 and 2.6 keV), and iron (6.7 keV). The x-ray spectra of supernova remnants like W49B can be used to determine the mass and composition of the material ejected in the supernova explosion, the total energy released in the explosion, the chemical composition and mass of the ejecta, and the nature of the progenitor star. The increased spectroscopic capabilities of ASCA will allow these parameters to be uniquely determined in detail for the first time.

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STARS AND GALAXIES

HIGH-RESOLUTION UV SPECTROSCOPY OF THE FLARE STAR AU MIC

A SMALL STAR about 30 light-years from the Earth is under study with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST). The star, AU Mic, is a red dwarf in the constellation Microscopium. It exhibits several short-lived disturbances, including large starspots associated with changing magnetic field strength. It erupts repeatedly and unpredictably, in stellar flares that are sometimes much larger than the flares on our Sun. Interest in AU Mic was fostered by a survey with the Einstein HEAO-2 satellite, which showed that AU Mic emits an exceptional number of x-rays. Two recent GHRS-based investigations were directed at investigating (1) the manner in which energy is transported down a loop of magnetic field at the onset of a stellar flare; and (2) the nature of the corona—the outermost atmospheric layer—of AU Mic, where the x-rays detected by the Einstein observatory are generated.

Each GHRS investigation required the study of ultraviolet light, which is not observable from the ground. The emissions sought are so weak that previous orbiting telescopes and spectrographs were not sufficiently sensitive to detect them. In the first GHRS investigation of AU Mic, the spectrograph was adjusted to sample a region of the spectrum at frequent intervals, so as to reveal changes that might occur during a stellar flare. The region was chosen to include the Lyman- α emission line of hydrogen at 1,216 Å and several other features. The purpose was to search for redshifted Lyman- α emission in the first moments of a flare. Radiation that is redshifted is received at longer wavelengths than those at which it was emitted. The usual cause of a redshift is the Doppler effect, according to which radiation emitted from a light source that is receding from the observer appears to be stretched so that its wavelength is increased; the faster the recession, the greater the redshift.

Redshifted Lyman- α radiation is predicted by the proton-beaming model of energy transport in flares. According to this model, a flare is initiated high on a magnetic-field loop in the corona of a star. Protons accelerated to high speeds in this event rush down the legs of the loop, so that, as seen from above, they are moving away. Passing through denser stellar gas, the protons collide with hydrogen atoms in a process called charge exchange, in the

process of which the protons capture electrons, and become high-speed, downward-moving hydrogen atoms. These atoms emit the Lyman- α line, which is observed as redshifted due to the downward (away) motion. Support for this theory came when GHRS detected redshifted Lyman- α radiation in a stellar flare on AU Mic. Further observations are planned to verify whether proton beaming occurs regularly as a significant energy transport mechanism in flares. The results may bear on the nature of flares on our own Sun.

In the second GHRS investigation of AU Mic, the spectrograph was adjusted to record ultraviolet emission from ionized iron atoms which have lost 20 electrons (Fe XXI). The ultraviolet light from AU Mic is very faint near the 1,354 Å wavelength of this iron emission, so it was necessary to combine the signals recorded over a total of 3.5 hours of observation in order to reliably detect this spectral feature.

The radiation from Fe XXI was detected in the GHRS observations, considered the first reliable detection of this emission in any star beyond the Sun. Analysis of the spectrum of Fe XXI and other spectral lines recorded by the GHRS indicates that the corona of AU Mic has a temperature of 10 million K, or 10 times the temperature of the corona of the Sun. Analysis of the GHRS data, together with supporting observations of AU Mic made with the IUE satellite, provides an astrophysical characterization of the atmosphere of the magnetically active red dwarf star, including information on the degree of turbulent motion. However, a definitive explanation for the heating of the stellar corona remains a challenge for future research.

Other contributors to this research included K. G. Carpenter of GSFC, R. D. Robinson and S. N. Shore (Computer Sciences Corp.), J. W. Brosius (Hughes STX Corp.), J. L. Linsky and A. Brown (Joint Institute for Laboratory Astrophysics), P. B. Byrne (Armagh Observatory, Northern Ireland), M. R. Kundu and S. White (University of Maryland), J. C. Brandt (University of Colorado), R. A. Shine (Lockheed Research Laboratories), and F. M. Walter (State University of New York, Stony Brook).

SPACE SCIENCES

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NEW DATA PROCESSING SOFTWARE LEADS TO THE DISCOVERY OF HIGH-EXCITATION LINE EMISSION IN THE GRAVITATIONAL LENS Q0957+561

GRAVITATIONAL LENSING is a phenomenon predicted by Einstein, and subsequently shown to be valid. Simply, light rays originating at a distant object, such as a galaxy, result in multiple ray paths as seen by an observer due to the gravitational deflection of light by an intervening object.

The well-studied dataset of the gravitationally lensed binary quasar 0957+561, obtained with the International Ultraviolet Explorer (IUE) satellite, was selected as a test case for the prototype of the New Spectral Image Processing System (NEWSIPS), which is under development at GSFC and the European Space Agency (ESA) Villafranca Satellite Tracking Station. This software system provides significantly improved reprocessing and calibration of IUE data. The application of NEWSIPS data-calibration software to existing datasets reveals the presence of far-UV, high-excitation emission lines and absorption from the hydrogen Lyman- β line not previously recognized based on the standard IUE data-calibration software system, IUESIPS.

In its 15 years of science operations, IUE has produced an heterogeneous archive that consists of more than 100,000 astronomical ultraviolet spectra. Begun in 1988, the Final Archive Program, a major undertaking by the IUE Project, is designed to enhance the signal-to-noise characteristics of IUE spectra, and create a homogeneous database of ultraviolet spectral images for this growing archive. The core of the Final Archive Program is based on the development of NEWSIPS to provide significantly improved calibration of archived images. The improved calibration should increase the signal-to-noise ratio of underexposed spectra by factors of two or three, compared with results achieved with IUESIPS.

Recent improvements in computer technology have enabled the application of sophisticated image processing techniques to IUE data which were not feasible when the original IUESIPS system was developed in 1976. In particular, NEWSIPS exploits the presence of a persistent underlying noise pattern that results from variations in light sensitivity across the IUE detector camera. By applying innovative algorithms to remove the so-called fixed-pattern detector noise from the raw science image, further sensitivity is achieved to observe weak spectral features not seen with IUESIPS.

Test runs with NEWSIPS on archival spectra of the gravitationally lensed quasar 0957+561 reveal the presence of high-excitation emission lines that were previously unrecognized. The large wavelength shift of spectral emission lines to the red—caused by the Doppler shift of light emitted by the quasar moving away from us due to the expansion of the Universe—is evidence that the distance to 0957+561 is cosmological in scale. Its measured speed of recession from Earth is roughly 66 percent the speed of light. For example, the resonance emission line of hydrogen Lyman- α , seen normally at $\lambda 1215$ Å in relatively nearby galactic sources, is Doppler shifted to $\lambda 2928$ Å due to the cosmological redshift.

Near the sensitivity limit of IUE, 0957+561 presents a doubled image of the quasar (the first figure, top panel) in the long-wavelength primary (LWP) spectral camera. As determined from ground-based observations, the double image of 0957+561 is formed by the action of a foreground cluster of galaxies that contains a giant elliptical Galaxy at the cluster center, which is at a distance roughly half that of the quasar. The close alignment of the quasar with the lensing cluster and observer produces a double image of 0957+561. The emission is formed by blends of numerous high-excitation emission lines and continuum emission emitted by the quasar. Absorption from Lyman- α and Lyman- β produce gaps in the emission continuum where indicated. In the bottom panel, a median filter smoothing is applied to the co-added image, which combines the



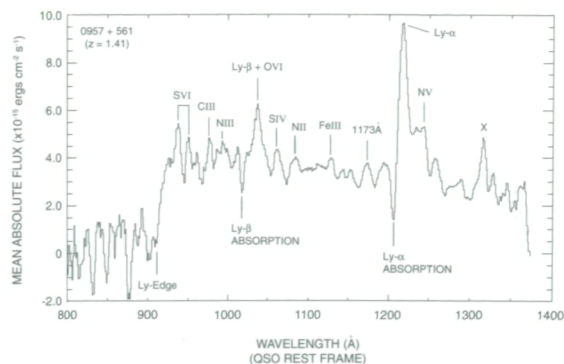
NEWSIPS-processed spectral image of the gravitationally lensed quasar 0957+561. The top panel shows the result of co-adding 10 IUE long-wavelength images.

signals of both spectra. This affords the unambiguous detection of emission from high-excitation atomic species.

Ten LWP spectral images obtained from the IUE archive of 0957+561 have been reprocessed with NEWSIPS and co-added so as to further enhance the signal (the first figure, top panel). Lyman- α line emission and absorption is present, as previously seen from IUESIPS-processed data. However, evidence of additional emission features at wavelengths considerably shorter than Lyman- α is indicated by data processed with NEWSIPS.

By next applying a smoothing (5-point median filtering) to the data, thereby effectively combining the signal from each spectral image, emission features corresponding to a variety of atomic species become apparent (the first figure, bottom panel). These include the emission lines of multiply ionized oxygen (O VI $\lambda 1037\text{\AA}$), sulfur (S VI $\lambda 937,950\text{\AA}$), carbon (C III $\lambda 977\text{\AA}$), nitrogen (N III $\lambda 992\text{\AA}$) and iron (Fe III $\lambda 1063-1073\text{\AA}$) which were detected with this method. In addition, absorption from the hydrogen Lyman- β line was also detected. This feature is formed by absorption of foreground neutral hydrogen clouds in the vicinity of the quasar which also produce Lyman- α absorption, as previously seen with IUESIPS-processed data. The Lyman- β emission line, however, is absent in IUESIPS-processed data because it is blended with the neighboring O VI line, which degrades hydrogen emission at this wavelength. The presence of O VI and S VI is particularly interesting because it suggests temperatures in excess of 1 million degrees in the vicinity of the central engine that powers emission from the quasar, and may indicate the presence of a black hole surrounded by an accretion disk.

The far-UV spectrum of 0957+561 is shown in the second figure, where the primary spectral features are identified after removing the redshift, thereby translating the spectrum to the rest frame of the quasar. As a result, spectral features now appear at their normal laboratory wavelengths. The sharp drop of far-UV continuous flux at the Lyman-limit at $\lambda 912\text{\AA}$ is due to a system of hydrogen clouds seen along the line of sight that are essentially at rest with respect to the motion of the quasar. Neutral hydrogen effectively absorbs nearly all continuous emission emitted by the quasar at wavelengths below the Lyman-limit flux discontinuity. The feature at $\lambda 1173\text{\AA}$ is a pseudo-emission line, formed by a combination of magnesium



The resultant smoothed IUE spectrum of 0957+561 plotted as intensity vs. wavelength after removing cosmological redshift to translate the spectrum to the rest frame of the quasar. Atomic emission lines arising from multiply ionized oxygen, sulfur, nitrogen, and carbon are indicated. Absorption from Lyman- β was detected using the NEWSIPS processing and co-addition of spectra.

absorption in the Milky Way and by silicon absorption (Si II $\lambda 1190, 1193\text{\AA}$) associated with the foreground lensing cluster of galaxies.

These first results suggest NEWSIPS is capable of revealing previously unrecognized information contained in the nearly 100,000 ultraviolet spectra in the current IUE archive, especially in spectra that are underexposed. Reprocessing the entire IUE archive in the next several years should stimulate considerable interest for IUE data in the scientific community.

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CONFORMAL GRAVITY AND GALACTIC ROTATION CURVES

IT IS BY NOW generally accepted that the correct theory of gravity, at least at the classical level, is that of general relativity, based on the well-known Einstein equations. Instrumental in acceptance of this theory has been its success in predicting the bending of light and of the precession of the perihelion of Mercury. These tests have established that the Newtonian $1/r$ potential is the correct, unique, non-relativistic approximation to the relativistic equations of the gravitational field of a spherically symmetric body. This implies the validity of the Newtonian force of gravity over all possible scales.

The validity of the Newtonian law of force is an experimental question which must be settled on observational grounds. Although all Solar System tests to-date are in agreement with such an approach, its validity on larger scales is not guaranteed. This validity is simply implied because of our belief in the Einstein gravity theory, which does not allow for additional terms in the gravitational potential.

On theoretical grounds, the inevitability of Einstein gravity is not guaranteed as derivable from a higher principle. In fact, the fundamental principle—the basis upon which it was derived, namely, general covariance—allows for an infinite number of such theories. General relativity is chosen from the infinite set only after additional assumptions are made. In particular, the relevant assumption is that the resulting equations must be of no higher than second order.

We are studying an alternative theory of gravity, one derived by challenging this latter assumption, based on both concrete evidence and fundamental theoretical reasoning. The assumption was made in order to give gravity parity with the other fundamental interactions which are made unique only after imposing a local conservation law, or, in technical parlance, a local gauge symmetry. Such principles are of fundamental importance in quantizing these theories. A conservation law chosen is that of local-scale invariance, a principle according to which the laws of physics are independent of the units locally chosen to measure physical quantities.

The price to be paid for the additional symmetry of the theory is that the resulting equations are of fourth rather

than second order, and hence, much more difficult to solve. Nonetheless, we have found exact solutions in this theory, now called Weyl gravity, since Weyl was the first to study the notion of scale invariance. These solutions are generalizations of those of general relativity, and indicate strongly that the Weyl gravity theory should enjoy the successes of general relativity on Solar System scales. On larger scales, the solutions to Weyl gravity include other terms besides the Newtonian potential. In particular, we found that a linear potential should make the dominant contribution to the potential of an isolated source.

Interestingly, the scales over which one expects this linear term to become dominant, thereby suggesting large deviations from the predictions of Newtonian gravity, are the scales of galaxies. It is well known that for galaxies there is a discrepancy between the observed rotation curves and those derived on the basis of the observed stellar distributions. This discrepancy has been remedied by the assumption of the presence of large amounts of dark matter, distributed in such a way as to force agreement with observations. Over the past year, we have used the potentials derived from the exact solutions to Weyl gravity to fit galactic rotation curves. It appears that the fits of the galactic rotation curves with these potentials are as good as those fit with dark matter, even though Weyl gravity allows much less freedom in those fits than does the dark matter theory. In particular, the flatness of the rotation curves comes about from a delicate balance between the linear and the Newtonian potentials, while the dark matter fits allow the distribution and the amount of dark matter to be arbitrary. The study and fits of galactic rotation curves is continuing.

This work is being done in collaboration with P.D. Mannheim of the University of Connecticut.

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GRAVITATIONAL N -BODY SIMULATIONS ON A MASSIVELY PARALLEL, SINGLE-INSTRUCTION/MULTIPLE-DATASET COMPUTER

MANY PROBLEMS in astrophysics require the solution of an N -body calculation, such as in the problem of N mutually gravitating bodies. Since the force of gravity falls off with distance as the inverse of its square, it is necessary to account for all the mass in the system when computing the acceleration on one individual particle. The force on a particle is found by adding all the forces due to its gravitational interaction with all other particles in the system. Therefore, the time to sum all the forces on all particles comprising the system scales as the square of the number of particles, and the problem becomes intractable for even the fastest computers if N (the number of particles) is large ($>1,000$ - $10,000$). Many problems of interest generally have particle numbers many orders of magnitude larger than this. For instance, the number of stars in a typical galaxy is on the order of 100 billion. To overcome this difficulty, some sort of an approximation is necessary.

In recent years, tree methods have been shown to be an efficient and accurate method for summing the forces among N gravitationally interacting particles. In this method, a hierarchical data structure is created (a tree) which groups the particles spatially. That is, near particles are grouped together to form a node, near nodes are grouped together to form a higher level node and so on, until a root node is reached which contains all of the particles. Each node is then linked to each of its child nodes through an indirect address or a pointer. This tree structure can then be efficiently searched.

For the purposes of gravitational N -body calculations, tree codes take advantage of the fact that the gravitational field of a group of particles can be treated as if all of the mass of that group of particles is concentrated in one massive point, provided that the point at which the field is being calculated is far enough from the group. Each particle can then traverse the tree data structure and select out the nodes which it may treat as a point mass based upon its distance from that node. If any node cannot be used, the particle proceeds to the child nodes through the links in the tree. This has the effect of greatly reducing the number of interactions which must be computed for any one particle as compared with directly summing the forces from all the particles.

Most tree codes have been implemented on serial machines (i.e., machines capable of performing only one instruc-

tion at a time). In recent years, large parallel machines have become available which show great promise in producing compute speeds that are well in excess of the fastest of today's serial computers when employed on many problems. Parallel computers are generally divided into two broad classes. The first is termed *multiple instruction, multiple data* (MIMD). In this case, each processor of the machine can execute a completely different instruction stream from all the other processors. Machines of this type consist of hundreds to thousands of processors, each with a memory capacity on the order of tens of megabytes (Mb). Some examples are the Thinking Machines' CM5 and the Intel Delta systems.

The second class, and the one for which we have targeted our implementation of a tree code, is termed *single instruction, multiple data* (SIMD). In this case, all processors execute the same instruction at the same time, but on different data items. SIMD machines generally consist of tens of thousands of processors, each with a memory on the order of tens to hundreds of Kbytes. The processors are typically more tightly coupled through communications than in MIMD machines. Therefore, the cost for fetching data which are not resident for a given processor is less. Some examples are the Thinking Machines' CM200 and the Maspar MP-1 and MP-2.

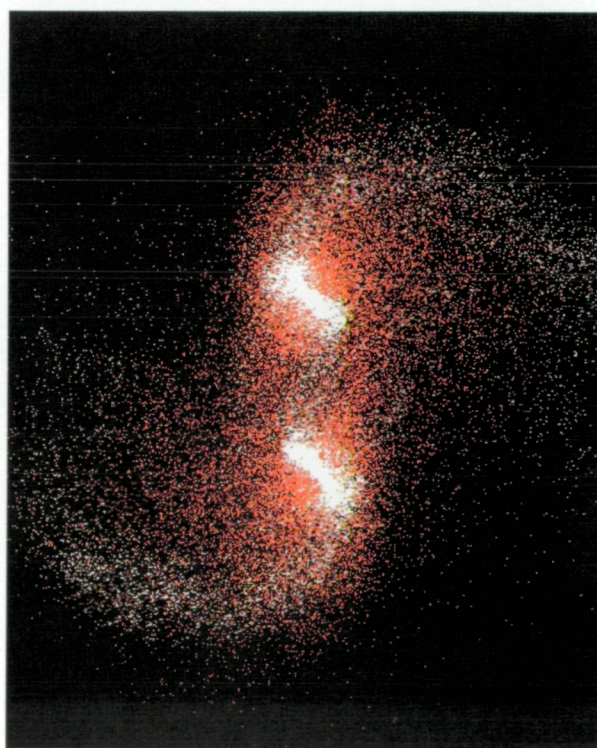
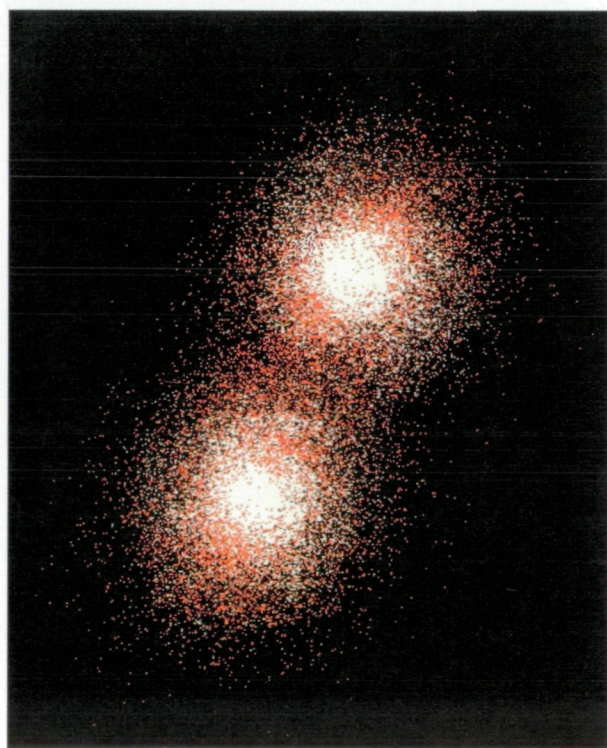
Parallel algorithms for tree codes do exist. These efforts have mainly focused on the use of MIMD architectures, and quite impressive results have been produced with them. Previous implementations of tree codes on SIMD machines, on the other hand, have been disappointing. For instance, one implementation on a Thinking Machines' CM-2 required ~5 minutes to sum the forces for a set of 32,000 particles. As a result, many have abandoned attempts at producing tree codes for SIMD machines. Further, the approaches used for MIMD machines are not practical for SIMD computer architectures which have a large number ($>10,000$) of small processors (memory per processor <100 Kbytes) since the memory is not available to store a large fraction of the tree data on any one processor. Consequently, data must be distributed across the processors in a fine-grained fashion, and data will have to be communicated more frequently. For computers like the Maspar MP-1, this need not be a large concern, since the communications latency is low compared to existing MIMD machines.



We have implemented a binary tree code on the Maspar MP-1 at GSFC. Our algorithm relies on fast, parallel sorts to build the tree. The particles are sorted in one of the coordinate directions (x, y, or z). The list is initially subdivided into two sublists which are exactly half the size of their parent list. These two sublists are then independently divided into a total of four lists. The process continues until the number of lists equals the number of particles. The divisions of these lists can be done in parallel, and the coordinate direction that is chosen on which to divide a list can be done independently of all the other list divisions. The coordinate direction on which to divide a sublist is chosen to be the direction which spans the largest physical range. This was done to maintain good spatial locality while at the same time producing an exact domain decomposition among the processors (i.e., the number of particles per processor is the same for all processors). Copies are stored on each processor of all the nodes which are ancestors of the particles stored in that processor. This helps eliminate data contention for higher levels in the tree. The tree-build phase of the algorithm is relatively fast, and requires only a small fraction of the total time cycle of building and searching the tree. For instance, the tree-build with 65,536 particles requires ~3

seconds, and with 1,048,576 particles requires ~63 seconds on a 16-k processor Maspar MP-1.

Since this tree is exactly balanced (i.e., each particle is paired with exactly one other particle), explicit links between parent and child nodes need not be stored but can be computed. This is done by associating each node in the tree with a number and a level. As each particle traverses the tree, a counter is associated with it that uniquely describes its location in the tree. If data are needed during this process which is off-processor, it is simply fetched over the communications network at the time it is needed. By doing this, we implicitly treat the distributed memory of the processors as if it was a global address space. This also helps simplify the programming task. Because of the high communications bandwidth of the Maspar MP-1, the cost for doing this is not great (~50 percent of the tree search is spent in communications). Overall performance is reasonably good for the tree search. For a uniform density sphere of particles, ~20 seconds were required to compute the accelerations for 65,536 particles; for the case of 1,048,576 particles, ~350 seconds were required. We also note that this implementation of a tree code is roughly the same speed required by



The two frames show the results of a simulation of a pair of gravitationally interacting disk galaxies.

a single head of a Cray Y-MP for a simulation of interacting disk galaxies. The results of this simulation are shown in the figure. The different frames show the particle positions for two different times. Each particle used in the simulation is plotted as a point. The 65,536 particles were used for this simulation. Each galaxy is modeled as having a disk and halo component. In the figure, the disk particles are shown as white and the halo particles, as red. The disk of each galaxy is supported against collapse by rotation. The halo component is supported by the random motion of its constituent particles. Each of these galaxies was given an initial position and velocity which placed them on an orbit which brought them close to one another at a later time. The two frames in the figure show the galaxies at times just before and just after closest approach.

Based on our experience, our view is that SIMD parallel processors should not be ruled out for problems of this type, especially considering their low relative cost as compared to vector supercomputers or large MIMD machines.

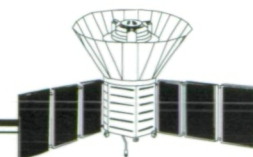
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Dr. Kevin M. Olson is a computational astrophysicist with the Universities Space Research Association, working in support of the High Performance Computing and Communications Initiative at the NASA Center for Computational Science located at GSFC. He works on developing numerical algorithms for solving physical problems on massively parallel computer architectures. His interests include Galaxy dynamics and star formation as well as the development and application of numerical techniques. He holds a PhD from the University of Massachusetts at Amherst.



SOLAR SYSTEM

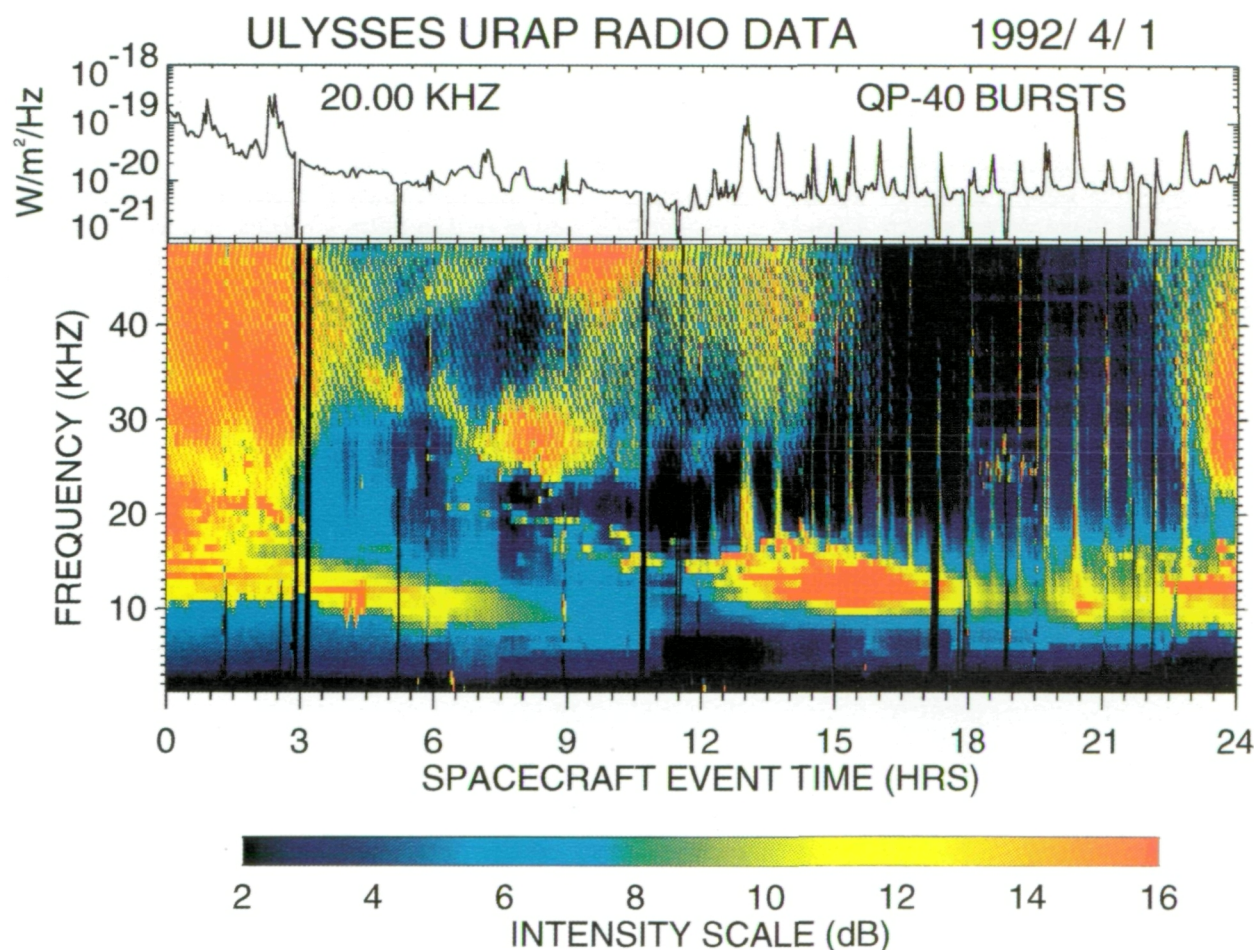
ULYSSES AT JUPITER: RADIO AND PLASMA-WAVE OBSERVATIONS

THE ULYSSES SPACECRAFT was launched in October 1990, on its mission to explore the interplanetary medium over the poles of the Sun. Ulysses, a joint mission of the ESA and NASA, will be the first spacecraft to visit these regions. To achieve a trajectory out of the ecliptic plane, the planet Jupiter was used to provide a gravitational assist. On February 8, 1992, Ulysses flew on a precise trajectory to within 450,000 km of Jupiter, thereby redirecting the spacecraft under the south pole of the Sun.

The Jovian flyby provided a wealth of observations of Jupiter's magnetosphere, particularly for the Ulysses

Unified Radio and Plasma Wave experiment (URAP). URAP is a series of instruments built by a collaboration of GSFC, the University of Minnesota, the Observatory of Paris-Meudon, and the French National Center for Telecommunications (CRPE). The Principal Investigator, Robert G. Stone, and six of the URAP co-investigators come from GSFC.

The design of the URAP instruments builds upon earlier discoveries made by the Voyagers, which encountered Jupiter in 1979. For example, because Ulysses is a spinning spacecraft, it is possible to determine the source di-



Twenty-four hours of Ulysses radio data acquired in April 1992. The upper panel shows quasiperiodic QP-40 bursts at 20 kHz; the lower panel is a display of all radio frequencies from 1 to 48 kHz, showing the diversity of Jovian radio emissions, including the QP-40 bursts.

rection from which radio emissions arrive. Using this technique, analyses of the URAP data show that the sources of several Jovian radio emissions are in the Io torus (a region of neutral and charged particles located in Io's orbit), on field lines passing through the Io torus, and in the auroral regions. Such determinations permit the radio emissions to be used as remote diagnostics of the source regions. URAP has also provided data on both the electric and magnetic fields of low-frequency plasma waves in the Io torus, confirming that they are of sufficient intensity to precipitate the particles responsible for some of the Jovian aurorae. The excellent sensitivity and frequency coverage of URAP were also used to measure electron densities and temperatures in various regions of the Jovian magnetosphere.

URAP has also provided important new discoveries that should play a key role in understanding the Jovian magnetosphere. These discoveries are due in part to the trajectory of Ulysses, which flew to high northern Jovian latitudes before passing through the Io torus into the southern Jovian hemisphere. For example, on the trajectory outbound from Jupiter, thousands of bursts like those shown in the figure were observed. These bursts exhibit an unexplained 40-min periodicity, and their occurrence rate is strongly dependent on the solar-wind velocity ar-

riving at Jupiter. Consequently, these bursts provide a remote sensing of solar-wind velocity at Jupiter.

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Dr. Robert MacDowall is a Co-Investigator on the Ulysses URAP experiment team. His research interests include solar and planetary radio emissions and planetary magnetospheres. He earned a BA with honors in Physics from Swarthmore College and a PhD in Astronomy from the University of Maryland. He has 12 years of experience at GSFC, including 2 years in the Planetary Magnetospheres Branch.

Dr. Robert G. Stone is the Principal Investigator of the Ulysses URAP experiment. He came to GSFC in 1962, after receiving his PhD from Yale University. His interests include solar, planetary, and galactic radio astronomy, and he has been Principal Investigator or Co-Investigator on more than a dozen satellite and rocket radio instruments. He is currently a senior scientist in the Laboratory for Extraterrestrial Physics.



LIGHT ION ESCAPE: IMPLICATIONS FOR THE EVOLUTION OF WATER ON VENUS

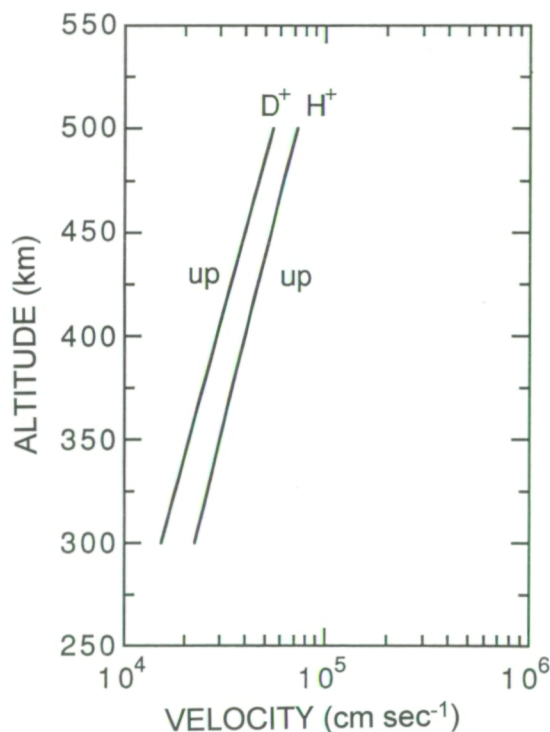
THE PIONEER VENUS ORBITER (PVO) mission ended October 8, 1992, as the spacecraft burned up in the atmosphere, completing almost 14 years of essentially flawless operations. The PVO spacecraft first explored the thermosphere and ionosphere of Venus to periapsis altitudes as low as 140 km, between December 1978 and July 1980. During this period, solar activity was at a maximum. Solar gravitational perturbations caused PVO's periapsis to rise out of the atmosphere for several years and then return in the fall of 1992, when periapsis penetrated the nightside thermosphere to altitudes below 140 km. Since solar activity was near a minimum level during this latter period, studies of the thermosphere and ionosphere of Venus under extreme solar activity became possible. The research reported here took advantage of this opportunity. We examined the relative importance of hydrogen and deuterium escape over the course of a solar cycle, allowing a more accurate evaluation of the evolution of water on Venus than had heretofore been possible. At the present time, Venus is very dry, possessing only a small amount of water in its atmosphere. This is surprising, because Venus was formed in the same part of the Solar System as Earth, with a similar size, mass, and chemical composition, and yet it possesses several orders of magnitude less water. The isotopic abundance ratio of deuterium to hydrogen yields some clues that address this apparent discrepancy.

Using the Large Probe Neutral Mass Spectrometer (LPNMS) and Orbiter Ion Mass Spectrometer (OIMS) measurements, a D/H ratio which was about 150 times the terrestrial value was found. This deuterium enrichment implies that hydrogen has escaped at a greater rate than deuterium as the atmosphere evolved. Indeed, it tells us that if only hydrogen escaped, then Venus would have had at least 150 times more water in the past than it has now. Clearly, the relative escape rates of hydrogen and deuterium are basic to the evolution of water on the planet. Recently, an escape mechanism for H^+ and D^+ ions which is similar to that of the terrestrial polar wind was identified; the resulting escape fluxes were found to be larger than other known processes.

Most of the H^+ and D^+ escape from Venus occurs on the nightside of the planet because the ions are much more abundant there. Electron and ion temperatures in the nightside ionosphere are a few thousand K. At these tempera-

tures, most electron speeds exceed the 10-km/s escape velocity and would escape from the planet if they had no charge. Instead, this tendency to escape produces an electron-ion charge separation, leading to a polarization electric field which efficiently accelerates the light ions H^+ and D^+ upward until they eventually escape.

At a given latitude and longitude, the upward fluxes of H^+ and D^+ in the ionosphere are essentially equal to the escape fluxes of these ions at higher altitudes (>500 km) in the ion-exosphere, where collisions are negligible and the ions readily accelerate to escape speeds. Fortunately, the upward fluxes of H^+ and D^+ in the ionosphere can be derived directly from relations for conservation of mass and momentum when they are expressed in terms of parameters measured by the PVO. The parameters required are the ion and electron densities and temperatures, the magnetic-field strength, and the vertical gradients for each.



Upward vertical flow velocities of H^+ and D^+ versus altitude, corresponding to averaged conditions in the midnight ionosphere of Venus.

This approach led to derivation of upward flow velocities for H^+ and D^+ (as shown in the figure), and the respective escape fluxes of $8 \times 10^7/\text{cm}^2/\text{s}$ and $3 \times 10^5/\text{cm}^2/\text{s}$ at 500 km. Since the escape only occurs from a small region on the nightside, the globally averaged fluxes are about $1.2 \times 10^7/\text{cm}^2/\text{s}$ and $4.3 \times 10^4/\text{cm}^2/\text{s}$ for hydrogen and deuterium, respectively. When this polar wind-like escape flux of hydrogen was compared with other known escape mechanisms, it was found that it is almost half the total globally averaged hydrogen escape flux of $2.75 \times 10^7/\text{cm}^2/\text{s}$. All of these fluxes are based on data obtained during the first 3 years of the PVO mission and, thus, correspond to escape rates for solar maximum conditions.

On re-entry of the PVO into the atmosphere in the fall of 1992, when near-solar-minimum conditions prevailed, the OIMS measured H^+ and D^+ densities that were more than an order of magnitude less than those observed during solar maximum. This strong solar cycle effect has a profound effect on the escape of hydrogen and deuterium from Venus; it implies that essentially all escape of these light gases occurs during solar maximum. Consequently, when the escape fluxes are adjusted for solar cycle variation, the globally averaged values are $1.4 \times 10^7/\text{cm}^2/\text{s}$ and $2.2 \times 10^4/\text{cm}^2/\text{s}$ for hydrogen and deuterium, respectively.

These escape fluxes were used by Donahue and Hartle to determine the implications for the evolution of water on Venus. Using the present water-vapor mixing ratio in the Cytherian troposphere, estimated to be in the range of 30 to 100 ppm, they found characteristic times of 190 and 630 million years, respectively, to exhaust such a water reservoir. If the escape occurs in the presence of sources of water such as those from comets or a mantle reservoir, then the characteristic time for decay of the initial D/H signature as D/H approaches steady state is between 1.4

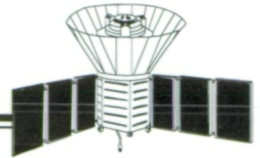
and 4.5 billion years. This would imply that present-day water vapor is nearing steady state if sufficiently strong sources of water exist. However, it can be shown that this process requires a source of water whose D/H ratio is only 1/7 the present-day value of 2.4×10^{-2} . This would appear to preclude comets as an important source of water, because their D/H ratios are in the neighborhood of a few times 10^{-4} , and would also require a highly fractionated source of water from a mantle reservoir. A more likely possibility for establishing the presently large value of D/H would be the fractionation of an early water reservoir by the selective escape of hydrogen over deuterium implied by the present-day escape rates. These values lead to an ancient water reservoir 340 times larger than the present atmospheric inventory, which is equivalent to 4.2 to 14 m of liquid water over the entire surface.

The PVO data analysis and interpretations were performed in collaboration with Dr. Thomas Donahue of the University of Michigan. Identification of the escape mechanisms was done in collaboration with Dr. Joseph Grebowsky of GSFC.

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THE WIND FROM THE SUN: THE SPARTAN 201 MISSION

THE SUN is the driving engine of the media in which NASA operates its missions and spacecraft. Located at the center of our Solar System, this magnetic variable star influences every cubic centimeter of interplanetary space from the Sun's surface to at least the orbit of Jupiter. The Earth is embedded in the outer atmosphere of this star, and our near neighborhood is modulated by the configuration and evolution of the solar magnetic field. For this reason, the organized, systematic investigation of the physics and astronomy of the Sun has been a national priority for the 4 decades of NASA's existence.

The wind of charged particles, both protons and electrons, which constantly escape the Sun's upper atmospheric levels and sweep past the Earth, is one solar phenomenon that NASA studies. This solar wind is sculpted by the solar magnetic field as this flux of material sweeps outward with velocities that range between 300 and 700 km/s. The wind interacts with the magnetic field of the Earth to produce variations in geomagnetism, aurorae, and disruption of communications and power distribution systems, both terrestrial and satellite. This flux of material appears to originate in the region of the solar corona, a region of hot, low-density plasma which composes the upper portion of the Sun's atmosphere.

To investigate further the physical properties of the region of the Sun giving rise to the solar wind, two instruments were selected in the early 1980s for flight on the Spartan reusable carrier which is designed to provide an extended observing opportunity from the Space Shuttle. The Spartan carrier system was developed by the Special Payloads Division of GSFC's Engineering Directorate.

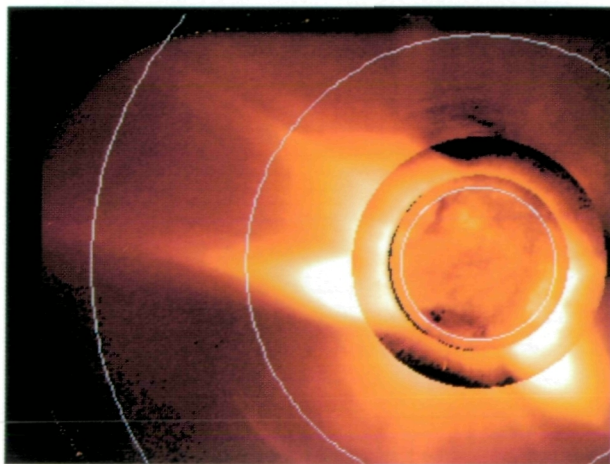
The two instruments are the Ultraviolet Coronal Spectrometer (UVCS), contributed by the Smithsonian Astrophysical Observatory of Cambridge, MA, and the White Light Coronagraph (WLC), constructed at the High Altitude Observatory of Boulder, CO, and now operated by GSFC. These instruments study the corona and its expansion into the solar wind in different but complementary ways. The UVCS uses short-wavelength radiation from the corona in order to investigate the temperature and density distributions of the protons and ions of the corona; the WLC investigates the distribution of electrons in the corona. Information from joint use of these two instruments allows the investigation of bulk flow in the corona, a property not previously observed.

Selected in the early 1980s, these instruments have a heritage of three sounding rocket flights in 1979, 1980 and 1982. The Spartan version of the UVCS is more sensitive than the rocket-class payload, and is capable of both higher spectral and spatial resolution. Observations are collected by making spatially resolved samples of the corona at both the line of neutral hydrogen (1216 Å) and at the doublet originating from five times ionized oxygen (O IV, 1032 Å and 1037 Å). Atmospheric absorption prevents terrestrial-based telescopes from operating at these wavelengths.

The WLC design is based on the coronagraph/polarimeter instrument flown on the Solar Maximum Mission (SMM) satellite, but it uses a CCD detector to improve the accuracy of photometric observations of the visible light solar corona. A linear polarimeter is built into this instrument to allow characterization of the two components of the solar corona. The first is the result of scattering of photospheric light by electrons in the Sun's atmosphere (K-corona); the other (F-corona) is the result of scattering of sunlight by dust particles by the interplanetary zodiacal cloud. Scattering by dust and atmospheric molecules in the Earth's atmosphere rule out the possibility of observing the corona at extended heights above the visible disk of the Sun from the surface of the Earth, excepting the special circumstance of a total solar eclipse, which has a duration not greater than 7 minutes maximum. Thus, the instrument payload of the Spartan 201 mission is optimally configured to investigate the physical characteristics of the extended solar corona and the originating region of the solar wind.

The payload was launched on the U.S. Space Shuttle *Discovery* on April 8, 1993, and the instruments and carrier were deployed outside the cargo bay for 44 hours (27 orbits) of observation. During this time, two types of large-scale features of the solar corona were the prime targets for the observing program. These features were the helmet streamer structures, usually associated with mid- to equatorial solar latitudes, and the high-latitude polar coronal hole structures. The latter are currently thought to be long-lived (months-long) sources of high-speed solar wind streams. At the end of flight operations, the Shuttle recovered the payload instruments and carrier, and returned them to Earth. Data from both instruments indicate flawless operation of the carrier and the instrument systems.

Data returned by the experiments flown in April 1993 are of excellent quality, and both instruments collected observations of both helmet streamers and polar coronal holes. Other investigator groups performed collaborative observing projects during the flight, and, as a result, the intense study of the solar corona by other research groups during the Spartan 201 operation has yielded an unusually comprehensive and broad view of the magnetic configuration of the Sun at the present phase of the solar activity cycle. For the first time, a comprehensive set of overlapping coronal data is available which allows the visualization of the solar corona from the surface of the Sun to a height in excess of five solar radii, 20 times the distance from the Earth to the Moon (see the figure). The lower corona (inner circular image) is shown as it appears in soft x-ray radiation. The intermediate heights of the corona are shown as observed in the near infrared by the imaging K-coronameter (annular image). The Spar-



The solar corona, April 11, 1993 composite image of three simultaneous observations showing details of the high-temperature solar corona from levels just above the photosphere (visible disk of the Sun) to a height in excess of five solar radii (7 million km). The Yohkoh soft x-ray image was supplied by the Japanese Institute of Space and Astronautical Science from the SXT experiment which is a Japan/U.S. collaboration involving the National Astronomical Observatory of Japan, the University of Tokyo, the Lockheed Palo Alto Research Laboratory, and NASA. The Mk-III image was supplied by the High Altitude Observatory of Boulder, CO.

tan 201 WLC image is used to demonstrate the extended portion of the solar corona. The north polar coronal hole is located at the top of the image and a classic helmet streamer extends to the left over the eastern limb of the Sun. The Yohkoh soft x-ray image was supplied by the Japanese Institute of Space and Astronautical Science from the Soft X-ray Telescope (SXT) experiment, which is a Japan/U.S. collaboration involving the National Astronomical Observatory of Japan, the University of Tokyo, the Lockheed Palo Alto Research Laboratory, and NASA. The Mk-III image was supplied by the High Altitude Observatory of Boulder, CO. Exciting preliminary results of these joint observing operations were presented in the summer of 1993, and a joint research effort by an expanded list of investigators is now in progress.

Refurbishment of the Spartan 201 carrier and the two instruments began in October 1993 for two additional Shuttle flights which are intended to collect correlative observations of the corona and solar wind near the Sun. These flights will augment data obtained by the ESA-NASA Ulysses spacecraft, which was launched in 1991, from *in situ* solar-wind measurements over the Sun's polar regions. The spacecraft's passage over the southern pole will take place in June through November 1994, and the satellite will pass over the north pole in June through September 1995. Two instruments currently under construction for the ESA-NASA Solar and Heliospheric Observatory mission (SOHO) are similar to the Spartan 201 scientific payload. Operation of this more sophisticated space system from a point in solar orbit will afford continuous viewing of the Sun and its features, as well as *in situ* sampling of the solar wind in interplanetary space. The operation of the SOHO version of the UVCS and the Wide-Field White Light and Spectrometric Coronagraph (LASCO) operations likely will be influenced by the results of the Spartan 201 missions.

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THE SOLAR, ANOMALOUS, AND MAGNETOSPHERIC PARTICLE EXPLORER MISSION

NASA's SOLAR, ANOMALOUS, and Magnetospheric Particle Explorer (SAMPEX) satellite, an international collaboration with Germany, is the first of a series of scientific research missions called Small Explorers. The Small Explorer concept was announced by NASA in 1988; in 1989, three missions were selected to examine energetic radiations observed near Earth and radio-frequency emissions emitted by stars in the early stages of development. The Small Explorer program concept places an emphasis on small spacecraft size and rapid (3 years or less) development for each mission.

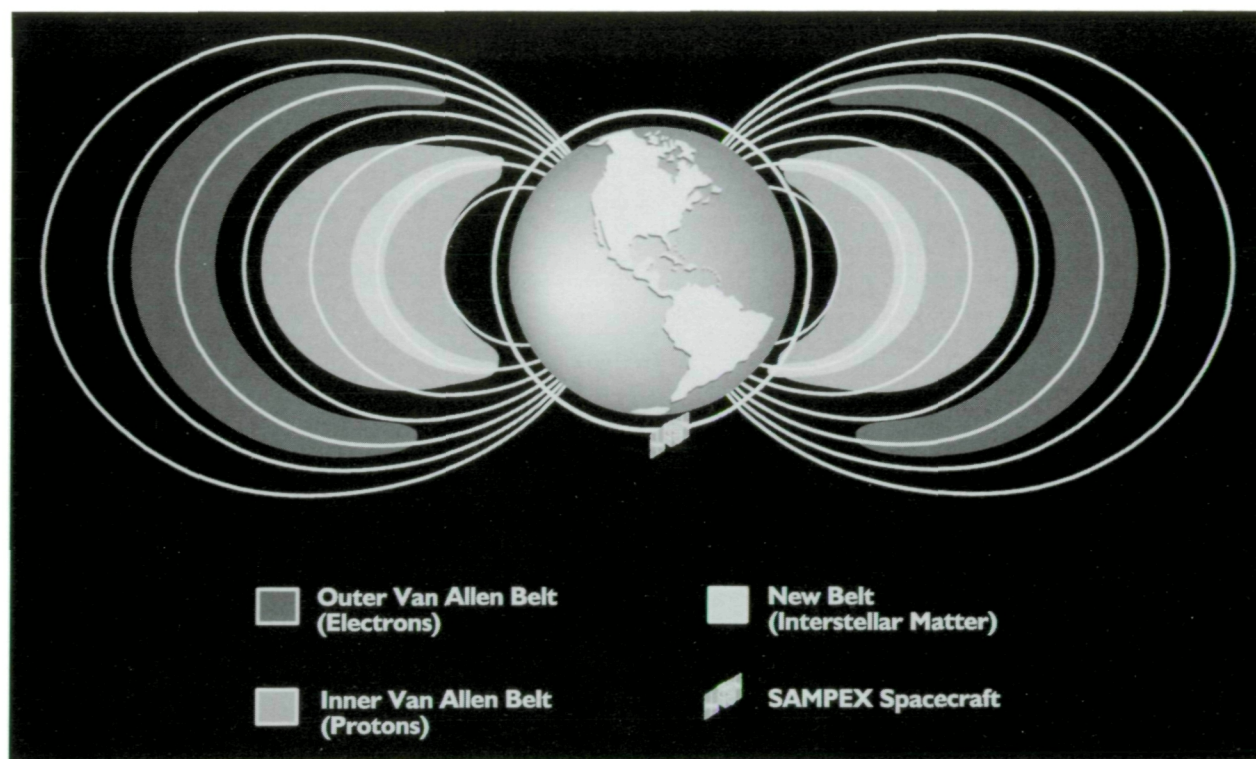
The SAMPEX mission is contributing new information on the high-velocity radiations arriving at Earth from the Sun and from interstellar space. These velocities range from 5 to nearly 100 percent the speed of light. The radiation SAMPEX studies consists of ions of such chemical elements as oxygen and iron, and also of electrons. These radiations have different origins in the Solar System and the Galaxy, and carry with them information about those origins. Researchers want to know more about these types of radiation since they can provide important information about our Sun and its interaction with the Earth, the local interstellar medium, and the violent explosions (supernovae) in the Galaxy. SAMPEX is named for the primary sources of the radiation: solar ions and electrons, which are swept up by huge explosions in the solar atmosphere; anomalous cosmic rays, which are believed to be interstellar gas atoms which are accelerated at the edge of the Solar System; and magnetospheric electrons, which plunge into the upper atmosphere and may influence its chemistry. SAMPEX also measures galactic cosmic rays: very high velocity ions which are believed to come from supernovae or pulsars. SAMPEX makes use of the Earth's magnetic field and new-technology instruments of unprecedented resolution and sensitivity to study features of these radiations heretofore inaccessible from earlier measurements.

SAMPEX has already made some remarkable discoveries. For example, the source and ultimate fate of electrons with energies greater than 1 million electron volts (MeV) confined in the outer regions of the Earth's magnetosphere have long been a puzzle. These electrons may be lost from the magnetosphere by moving along magnetic field lines, and then penetrating the Earth's atmosphere at mid to high latitudes. The interaction of these precipitating electrons

with the atmosphere at altitudes near 50 to 70 km initiates ion-chemical processes which lead to the formation of oxides of nitrogen—compounds important to the balance of the Earth's global ozone levels.

The highly inclined (82°) polar orbit, the ability to acquire measurements at all longitudes, and the significant mission lifetime (at least 3 years) provide the SAMPEX mission with an unique opportunity to make direct measurements of magnetospheric electron radiation and of electrons penetrating the atmosphere. Such measurements are now beginning to firmly establish the extent to which this phenomenon provides a strong and continuing coupling between variations in the solar wind, modulations of the near-Earth space environment, and middle atmospheric processes. Previous studies have shown that the variation of high-speed plasma flows (the so-called solar wind) emanating from the solar corona modulates the amount of these energetic electrons within the magnetosphere. Over the course of an 11-year solar activity cycle, time-averaged electron radiation levels observed at geostationary orbit altitudes have varied by up to 800 percent, with peak electron levels occurring during solar activity minima. Such radiation variations have been used to estimate the number of electrons penetrating the atmosphere. Based on these penetrating radiation levels, results derived from an atmospheric model have suggested that large-electron-level variations in the outer magnetosphere may lead to a significant change of global levels of mid-atmospheric odd-nitrogen compounds, and (through complex catalytic cycles) to changes in global ozone levels.

In the realm of high-energy ion measurements, SAMPEX has also located a new radiation belt surrounding the Earth; one that traps material from the nearby interstellar medium. The new belt, which dips closest to Earth over the South Atlantic Ocean, is embedded in the lower of the two previously known Van Allen belts (see the figure). In 1991, a team of Russian and U.S. scientists detected this cloud of nuclei trapped in the Earth's magnetic field, but they were unable to fix its location. SAMPEX has pinpointed the location of the new belt (the existence of which was first predicted 15 years ago) and is now monitoring its intensity variations and analyzing its composition. The new belt consists of trapped heavy ions, including the nuclei of atoms of nitrogen, oxygen, and neon, which are



The newly discovered radiation belt around the Earth is shown as a dark gray crescent. The Van Allen belts are represented by lighter gray crescents.

part of the anomalous cosmic-ray component. These gases are also components of the thin (less than one atom/cm³) cloud that fills the void between stars in the Milky Way. This material, called the interstellar medium, is the debris from the birth and death of stars, and particles that have been drifting since the formation of the Universe some 15 billion years ago. Some of these interstellar gases penetrate the heliosphere (i.e., the vast cloud of particles trapped in the Sun's magnetic field). They can then be accelerated by the solar wind and by the termination shock at the edge of the Solar System and end up trapped in the Earth's magnetic field. Once inside the new belt, these atoms may bounce back and forth between the Earth's magnetic poles for weeks before leaking out into space or into the atmosphere. As a result, the amount of matter inside the new belt varies with time (e.g., it doubled between August and November 1992). The belt is most intense above an 8,000-km strip of Atlantic Ocean between the southern tips of South American and Africa. The radiation is most intense along this strip because the Earth's magnetic field is not centered perfectly, and this is where

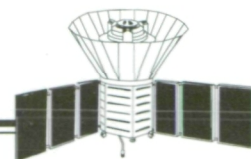
it allows the trapped particles to get closest to the Earth's surface. This off-centeredness can be seen in the figure. Note that the belts on the left appear slightly farther away than those on the right.

SAMPEX has demonstrated that small, relatively inexpensive satellites can return large scientific benefits. SAMPEX should continue to return data for much of the present solar cycle before it re-enters the atmosphere in 1997 or 1998.

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HYBRID SIMULATIONS OF COLLISIONLESS MAGNETIC RECONNECTION AND ELECTRON PRESSURE ANISOTROPY

MOST OF THE PLASMAS (completely ionized gases containing equal numbers of electrons and positive ions) which occur in the space environment are highly collisionless (i.e., the orbits of charged particles in the ubiquitous magnetic and electric fields are little modified by particle-particle interactions). On a more global scale, the collision-free nature of the plasma implies that the magnetic field is frozen into the plasma flow (i.e., that the plasma flow carries with it forever magnetic flux that threaded it once). Under these conditions it is clear that, for example, solar-wind plasma could not enter the magnetosphere since it would have to drag the interplanetary magnetic field into the Earth's magnetosphere, which already consists of topologically different flux originating from the Earth's dipole.

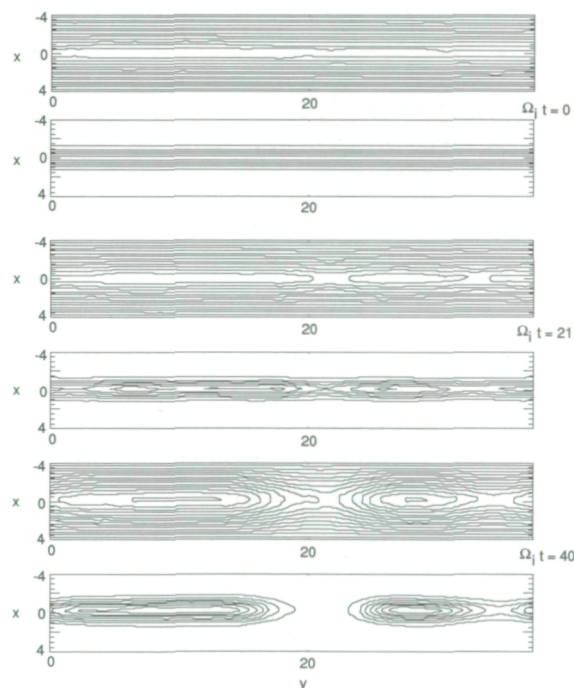
Nature's most effective way out of this dilemma is called magnetic reconnection, or just reconnection. Magnetic reconnection allows this forbidden transport by inserting only a local violation to the collision-free condition, in the so-called diffusion region. In this region, magnetic field lines can become first disconnected and later rejoined, and the plasma can locally move independent of the magnetic field. Through this effect, magnetic reconnection provides the large-scale transport required to explain phenomena such as the presence of solar-wind plasma in the magnetotail, or the ejection of large-scale coherent structures containing plasma and magnetic field, named plasmoids, from the magnetotail. In spite of the observational successes of the reconnection model and theoretical analyses demonstrating the need for dissipation processes and certain electric fields in the dissipation region, how reconnection actually occurs on a microscopic level in a collisionless plasma remains a much debated topic.

In principle, there are two, not necessarily mutually exclusive, mechanisms that could support magnetic reconnection by providing particle scattering in the dissipation region. Both require the presence of current sheets (i.e., extended regions where moving charged particles maintain a sheet-like electric current which generates a magnetic field). Current sheets are quite commonly found in space and laboratory plasmas.

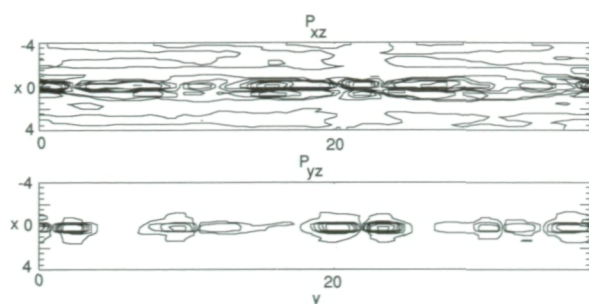
The first mechanism is tied to the fact that regions of high electrical current (i.e., of large relative velocities between ions and electrons) can become the locus of a variety of

micro-instabilities involving plasma waves. Wave-particle interaction can then lead to scattering of the current-carrying particles, causing effects reminiscent of macroscopic collisions and resistivity. These anomalous collisions cause electric fields which can, in principle, support an electric field suitable for reconnection.

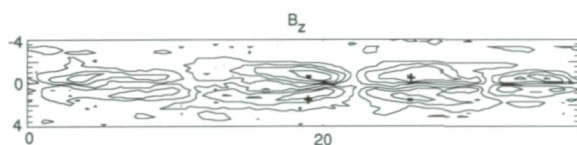
The other mechanism is based on particle inertia. Under certain conditions, an instability can occur through the mutual attraction of current filaments inside the current sheet. The ion inertia, due to the much larger mass of ions, plays the dominant role here. The instability causes a redistribution of electric current, and, hence, a reorganization of the magnetic field that is generated by the current. In this field, ion orbits are changed in a way to enhance the current clustering. For reconnection, however, the electrons need to be able to follow the ions, since otherwise



Magnetic field (first, third, and fifth panels) and ion density (second, fourth, and sixth panels) for the initial condition, and two subsequent times. The figure shows the formation of reconnection regions and the ejection of the ion populations. The times shown are in inverse ion cyclotron periods; the length unit is an ion gyro radius.



Spatial distribution of the relevant electron pressure anisotropies: P_{xz} (top panel), and P_{yz} (bottom panel).



Quadrupole-like variations of the normal magnetic field component B_z in the vicinity of the major reconnection region.

large space charge electric fields result which would throttle the instability process. A scattering mechanism is, therefore, required to redistribute the electrons across the magnetic field. It can be shown that this mechanism is given by the electron inertia inherent in the noncoherent thermal particle motion in the vicinity of the diffusion zone. In terms of electron fluid properties, if the electrons are not quite evenly distributed around the magnetic field, suitable electron diffusion takes place.

To study the latter process in greater detail, a suitable numerical simulation model needed to be devised. We have therefore, for the first time, employed a two-dimensional hybrid simulation code which treats the ions as particles, and includes the ion instability mechanism discussed above. The electrons are modeled through a massless fluid which can develop anisotropies according to a realistic new pressure model.

For simplicity, the initial configuration is chosen to be a current sheet separating two regions of oppositely directed magnetic fields, with a typical width of one to a few ion gyro radii. This configuration is of particular relevance in the magnetotail of the Earth, where similar structures occur shortly before substorm onset, as evidenced by satellite data. The first figure shows the magnetic field lines

and ion density of the initial and two later configurations. It can be seen that, during the evolution, the magnetic field lines become newly connected at a variety of locations, one of which becomes dominant during the later part of the evolution. The density appears to be depleted at the reconnection sites, from which particles have been ejected by electric fields. The second figure displays the two most important components of the electron pressure relationships. It can be seen that these pressure components form primarily in the vicinity of the major reconnection region.

The simulations also show significant electron flow away from the reconnection regions along the current sheet and toward the reconnection region in the direction perpendicular to the current sheet. Associated with this electron flow, which represents a current, is the generation of a typical quadrupole-like magnetic structure involving the magnetic field component perpendicular to the plane shown in the first figure. This structure is displayed as contours in the third figure. Here we also find a localization in the vicinity of the reconnection region by typically a few ion gyro radii.

Both of these signatures are unambiguous indicators of a magnetic reconnection process operating in the vicinity. Apart from electron effects, the resonant ion interaction with the changing magnetic and electric fields also produces characteristic signatures in the ion distribution function. Furthermore, ion beams emanating from the reconnection region are formed; these deserve further study. The future of this work will involve large-scale simulations of configurations closely resembling the Earth's magnetotail, as well as direct interactions with relevant observations, such as provided by the International Sun-Earth Explorers (ISEE) 1, 2, and 3, and the Geotail spacecraft.

This work has been done in collaboration with D. Winske, Los Alamos National Laboratory.

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FORMATION MECHANISMS AND INTENSITIES OF THE SOLAR HE 304 Å LINE

ONE OF THE MOST important spectral lines formed in the Sun's atmosphere is the 304 Å line radiated by the once-ionized atom of helium, He II. The 304 Å line is important in that it dominates the radiative losses from an important part of the solar atmosphere and the processes involved in its formation give us insight into other regions of the atmosphere. Once we understand the roles of these processes, we will be able to assess changes in the variation of relative helium abundance with height in the solar atmosphere, which, in turn, will allow us to address more fundamental questions of helium abundances in other stars and in the cosmos in general.

A longstanding problem in solar physics has been the mechanism of formation of the 304 Å line. For over 3 decades, there has been controversy over whether this line was energized primarily by collisions between the He II ions and ambient free electrons, or whether the primary source of energy for this line was back radiation from the overlying solar corona. This problem is often described as evaluating the relative strengths of collisional excitation and photoionization-recombination (p-r) in the formation of the 304 Å line. Also, based primarily on assessment of radiative transfer effects, the total intensity observed in the line is greater than current theoretical calculations have predicted.

To address this problem properly, it was necessary to obtain a good set of data on the 304 Å line itself, as well as on coronal radiations that would provide the basis for estimating their contribution to the line formation. Since the line formation process was already known to depend upon physical conditions that could vary strongly from one kind of solar region (quiet Sun) to another (intense active region), it was important that the dataset of the 304 Å radiation contain both images of the solar features to be studied and also adequate line profiles for estimating the total line intensity. All of these data also had to be obtained above the Earth's atmosphere.

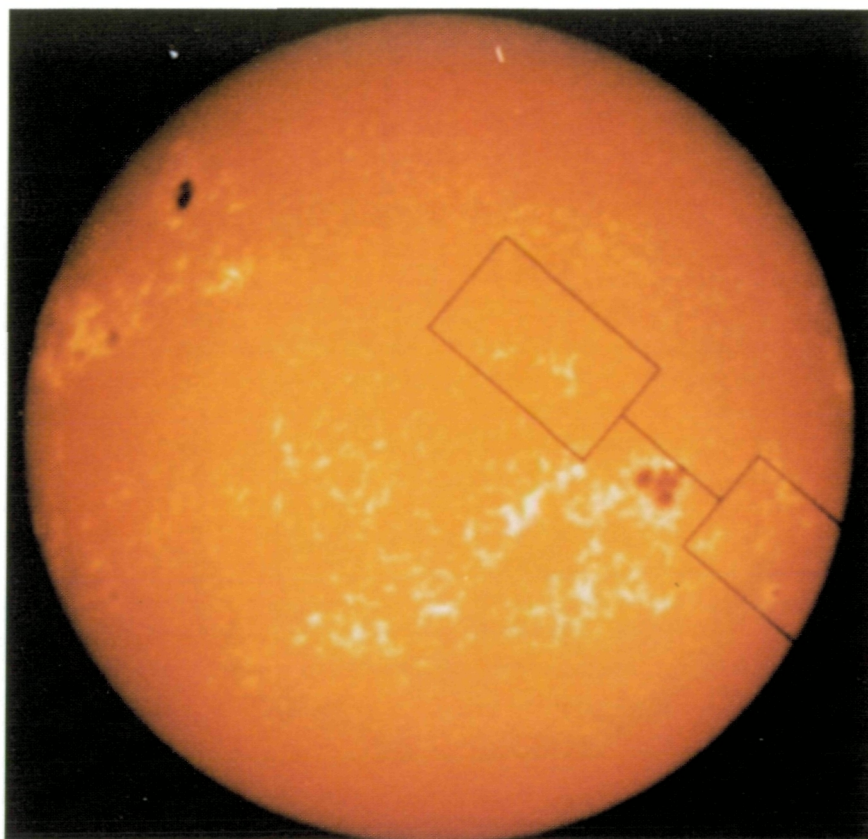
These data requirements were met by the Solar Extreme Ultraviolet Telescope and Spectrograph (SERTS) designed and built by the solar physics group at GSFC and flown successfully on May 5, 1989; May 7, 1991; and, most recently, on August 17, 1993. By means of an hourglass slit, illustrated in the first figure as a projection on the Sun in one of the pointing positions selected for the 1991

flight, images were obtained with the two wide lobes at the ends of the slit, while spectra were obtained with the narrow slit in the middle. A change in the pointing position during the flight allowed images to be made of the locations at which spectra had previously been taken, and vice versa.

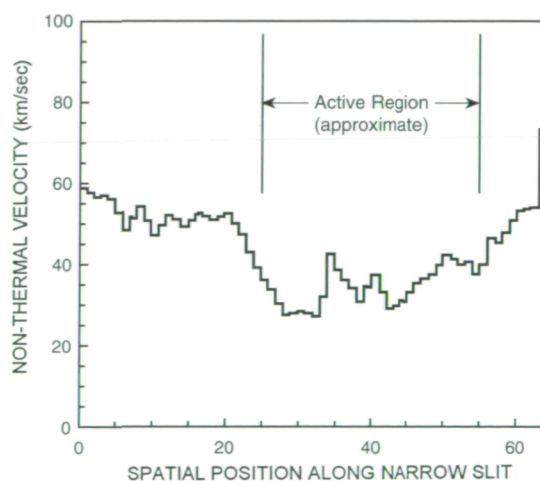
The general appearance of the Sun during the second flight appears in the first figure. The second figure is a plot of the corresponding 304 Å nonthermal line width, expressed as a nonthermal velocity, as a function of position along the narrow slit. The data from the 1989 SERTS flight have a similar appearance, and cover an almost identical wavelength range.

To determine the relative contributions of electron collisional excitation and coronal p-r to producing the 304 Å line, it was necessary to estimate the coronal radiative flux energetic enough to ionize the He II ion from the observed coronal lines. Fortunately, Skylab data show that the total coronal radiative flux scales almost linearly from quiet Sun to intense active regions with the strong 335 Å and 361 Å lines of the Fe XVI ion. These are lines for which we had excellent, spatially resolved, calibrated spectra. Thus it was possible to proceed with a computation of the relative strengths of the two competing line-formation mechanisms, by applying standard, non-LTE theory for the formation of an optically thick spectral line in a low-density atmosphere to obtain a simple expression for the ratio of the collisional excitation rate to the rate of the p-r process, expressed as a function of the observable parameters, and most significantly, of the strength of the coronal radiation field. The result we obtained was that collisional excitation of the 304 Å line is overwhelmingly dominant over the quiet regions of the Sun and probably over most active regions, but the p-r process may become important in intense active regions, and is almost certainly important in flares.

Using this result, we gained important insight into why current theoretical calculations have always underestimated the total intensity of the 304 Å line. These calculations have so far failed to make full allowance for the effect of small-scale nonthermal velocities called microturbulence, in the line formation region. Yet, as demonstrated in the second figure, this omission is serious. The lowest values of the nonthermal velocity occur where



Spectrograph entrance slit superimposed on a Ca II K-line image of the Sun taken at Big Bear Solar Observatory at the time of the May 7, 1991 flight of SERTS.



Plot of He II 304 Å nonthermal line width, where the thermal and instrumental line widths have been removed from the observed line width, as a function of position along the narrow slit, in the case where this slit lay across an active region (identified) during the May 7, 1991 flight of SERTS. Further investigation revealed that the total line intensities of the 304 Å line are strongly anticorrelated with nonthermal line widths in these observations.



the line intensity is *highest* (the active region in the second figure), and vice versa. A well-known effect of radiative transfer in an optically thick line (e.g., the 304 Å line) is to broaden the line. Yet in the second figure, the observed nonthermal line width is greatest in the quiet Sun where the 304 Å intensity is relatively *low*. Therefore, this cannot be primarily a radiative transfer effect. Much of the measured nonthermal line width in the quiet Sun must arise from physical microturbulence.

If we assume that only half of the nonthermal line width represents microturbulence, a straightforward computation shows how far the He II ions would migrate from the region in which most of them are produced before they are collisionally excited by electrons and radiate in the 304 Å line. This yields a sufficient flow of He II ions upward into a region of hotter (higher temperature) electrons to increase the integrated 304 Å line intensity up to observed values in the quiet Sun.

The authors would like to acknowledge the contribution of William T. Thompson of the Applied Research Corporation for reducing much of the flight data and for generating the images obtained from the 1989 flight.

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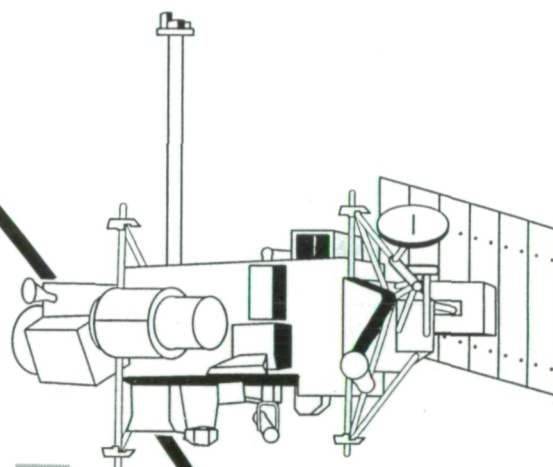
Dr. Stuart Jordan is a senior staff scientist with the Laboratory for Astronomy and Solar Physics (LASP), whose primary interests are the heating and dynamics of the outer solar atmosphere. He is currently a SOHO Co-Investigator, and holds a PhD in Astrophysics from the University of Colorado.

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EARTH SCIENCES

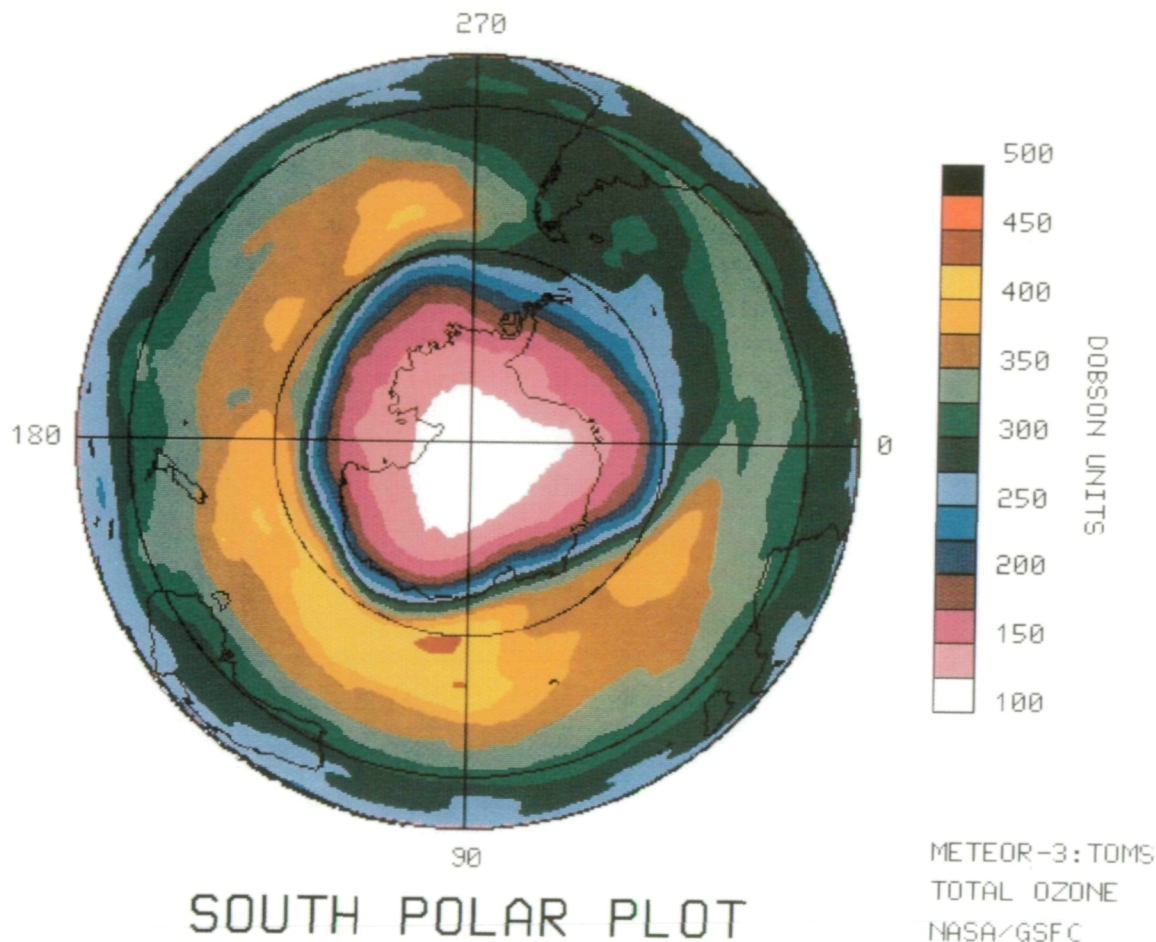


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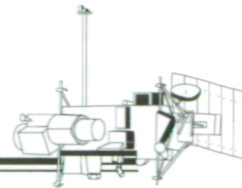


TOMS/METEOR-3 IMAGE

This false-color image shows the total ozone in the Southern Hemisphere for October 6, 1993. Preliminary total ozone values on this day were less than 100 Dobson Units, a new record low in a region near the South Pole. The total ozone values were measured by the Total Ozone Mapping Spectrometer (TOMS) instrument aboard the Russian Meteor-3 satellite, launched in August 1991. The color scale at the right-hand side of the figure shows the total ozone values.

The Antarctic ozone hole is located in the center of the figure and is indicated by the blue, magenta, and white colors. Prior to 1975, values of total ozone between 250 and 300 Dobson Units (light blue to dark green) were normal, indicating a decrease of about 150 Dobson Units.

The TOMS program is managed by NASA's Goddard Space Flight Center, Greenbelt, MD, for NASA's Office of Mission to Planet Earth, Washington, DC.



EARTH SCIENCES

NASA'S CONTRIBUTION to the U.S. Global Change Research Program is termed *Mission to Planet Earth*. The Goddard Space Flight Center and its Earth Sciences Directorate carry a large fraction of the responsibility for the conduct of the Mission to Planet Earth. In meeting this responsibility, a full spectrum of research activities is being conducted that compiles and analyzes observations from spaceborne, airborne and ground-based instruments, and develops models that effectively utilize these observations in order to better understand and quantify processes and trends occurring in Earth-atmosphere systems.

During the last year, several areas are worthy of note in typifying the progress in observational data compilation and analysis, and modeling related to global and regional processes and changes. Observations acquired from the total ozone mapping system and the Upper Atmosphere Research Satellite (UARS) have provided greater understanding of processes related to the distribution of chemical constituents in the upper atmosphere and a quantitative documentation of decade-long trends in total ozone. The latter data have contributed to regulations affecting the use of chlorofluorocarbons. Analyses of satellite, aircraft, and ground-based data from the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment were completed to the point of publication of results showing that the surface flux from the Earth's surface to the free atmosphere was twice as large as expected, based on previous work. A 4-month experiment in the western tropical Pacific conducted as part of the Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE) revealed that low-level, small cloud structures provided a larger portion of the major latent heat release in the tropics than was previously thought to be the case. Modeling efforts also indicate that surface evaporative cooling of the ocean may be a major factor acting as a thermostat for maintaining the stable, uniform warm-pool ocean surface water in the western Pacific. A world-wide historical database

acquired through the Crustal Dynamics Project and recently completed now facilitates continuing research on motion of the large plates of the Earth.

The description of the major areas of research accomplishment given in the previous paragraph is supplemented in more detail by the articles that follow in this *Research and Technology Report*. The first four articles deal with the modeling of processes. These articles describe what can be achieved through advanced modeling techniques in terms of understanding, for example, the influence of external forcings due to the Sun and to anthropogenic influences, changing boundary conditions such as land and ocean temperatures, sea-ice cover, etc., and the subsequent effects on moisture and precipitation distribution and the dispersion of pollutants. The next thirteen articles describe a wide array of data analysis and modeling efforts that offer further insight on the progress being achieved in utilizing observations, principally from remote sensing instruments, to quantitatively describe processes occurring on the Earth or in its atmosphere. The aspects studied include those dealing with precipitation and water-vapor estimates, variations in the radiation budget over the tropics associated with variability in atmospheric water vapor and clouds, changes in ice sheets, sea-ice cover, ozone, forest biomass, and impact cratering.

Overall it is rather clear that this is an exciting and challenging time to be involved in Earth sciences research. Not only are data sets being compiled that are comprehensive in space and time, but also models are progressively being improved so as to better depict Earth system processes and trends. With the development and evolution of the expected Earth Observing System, complementary Earth Probes, and the associated data and information systems scheduled for the latter part of the 1990s and into the 21st century, this sense of excitement and accomplishment should be expected to increase further as improved understanding is achieved. This understanding is coupled with practical use for policy decisions related to adapting or mitigating the effects of environmental change.

Vincent V. Salomonson

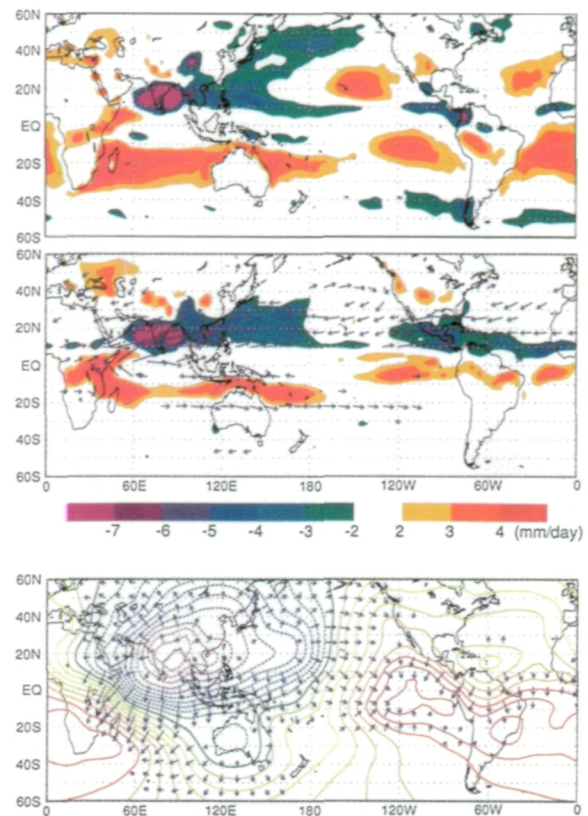
PROCESS MODELING

SEASONAL TRANSITION OF GLOBAL CIRCULATION SIMULATED BY THE GODDARD EARTH OBSERVING SYSTEM GENERAL CIRCULATION MODEL

GENERAL CIRCULATION MODELS (GCMs) are often used to understand and predict climate change; the model-produced data provide invaluable information for understanding the physical processes maintaining the general circulation. The Data Assimilation Office recently improved the tropospheric version of the Goddard Earth Observing System (GEOS) GCM for the purpose of global data assimilation.

The global climate of the decade 1979 through 1988 has been simulated with the GEOS GCM using the observed monthly averaged distribution of sea-surface temperature (SST) and sea ice as boundary conditions. The resolution used is 4° latitude by 5° longitude horizontal, and 20-sigma (σ) levels vertical. Model climatology is crucial in climate data assimilation, particularly over regions with sparse observations. Hence, evaluation of model climatology and variability provides important information to help us comprehend the assimilated data product. This decadal simulation is also part of an international effort to determine systematic climate errors in state-of-the-art atmospheric models.

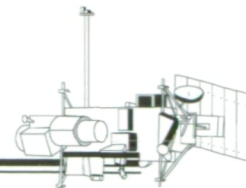
In the atmosphere, the moisture content is balanced by the moisture exchange between the land-ocean surface and the atmosphere through evaporation and condensation processes. The top part of the figure shows evaporation minus precipitation (E-P) for the Northern Hemispheric summer (June/July/August, JJA) climatology simulated with the GEOS GCM, which identifies the global distribution of the atmospheric moisture source and sink regions. The Indian subcontinent region is the most pronounced moisture sink due to the monsoon rainfall; the subtropics are the major moisture source due to standing subtropical highs. In the middle part of the figure, the seasonal transition of E-P from the Northern Hemispheric spring (March/April/May, MAM) to summer (JJA) indicates that the excessive moisture sink in the Indian monsoon region and the increased moisture source near the Somali coast are the outstanding features which develop rather abruptly between seasons. The seasonal transition of the vertically integrated moisture transport from the Northern Hemispheric spring to summer, represented by vectors, indicates that the intensified Somali jet in the lower troposphere transports the enhanced moisture sup-



Top: seasonal mean E-P for the Northern Hemispheric summer simulated by the GEOS general circulation model. Middle: seasonal transition of E-P and the vertically integrated moisture transport (vectors) from the Northern Hemispheric spring to summer. Bottom: seasonal transition of the 200-mb velocity potential and the divergent component of winds (vectors) from the Northern Hemispheric spring to summer.

ply in the South Indian Ocean and East African region toward the Indian subcontinent. The restless process of the moisture exchange through the evaporation and condensation in the monsoon region supplies a tremendous amount of latent heat energy to the atmosphere.

The seasonal transition of the 200-mb velocity potential and the divergent component of wind vectors in the bottom part of the figure indicates that the most pronounced



increase in the upper level outflow is located over the Indian monsoon region centered around the Bay of Bengal. The seasonal migration of the upper level divergent center is mainly due to the most active convective activities related to the maximum ocean surface temperature in the tropical western Pacific. It is interesting to note that latent heating related to the monsoon rainfall has a more pronounced impact on the seasonal transition of the divergent flow than does the ocean surface temperature change in the western Pacific. The significant seasonal transition is also found in the eastern tropical Pacific, eastern South America, and the west coast of South Africa, with enhanced upper level convergence. The seasonal transition patterns identify the atmospheric teleconnection between the Eastern and Western Hemispheres, with the dominant modulation in the monsoon region.

The seasonal climatology and transition patterns reflect the capability of the GEOS GCM to simulate the seasonal variations of the monsoon circulation. The monsoon region is the most pronounced moisture sink and the largest latent heat energy source. The level of energy exchange in the monsoon region depends on the intensity of the monsoon circulation, which is also sensitive to underlying ocean surface conditions. The monsoon rainfall is crucial for the local economy; it also has a significant impact on the global climate through atmospheric teleconnection. The connection between abnormal monsoon circulation and North American climate has also been indicated in a number of studies. The fluctuation in the monsoon evolution must be an important factor responsible for the interannual and intraseasonal variations of the local climate over various regions. The results found in this decadal simulation will be verified with the information from the 5-year global data assimilation carried out in the Data Assimilation Office, Laboratory for Atmospheres.

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Sponsor: Office of Mission to Planet Earth

Dr. Richard Rood, Head of the Data Assimilation Office, is an atmospheric scientist specializing in global transport processes. He is currently leading the global data assimilation effort at GSFC. He earned his PhD from Florida State University. During more than 11 years of atmospheric research at GSFC, Dr. Rood received the Laboratory for Atmospheres Support Award, the NASA Quality Increase Award, and the NASA Performance Award.

Dr. Chung-Kyu Park does research on the climate dynamics of global circulation. He utilizes general circulation models to examine low-frequency variability and predictability of global circulation. Dr. Park has 6 years of experience at GSFC. He earned his PhD in Atmospheric Sciences from the University of Missouri.

Ms. Andrea Molod has been working on general circulation model development at GSFC for 9 years. Her special interests include convection and cloud/radiation feedback parameterization and atmospheric hydrological processes in the model. Ms. Molod received her MS in Meteorology from the University of Maryland.

Mr. Lawrence Takacs coordinates the development and maintenance of the general circulation model at the Data Assimilation Office. He is also a principal investigator of numerical schemes for the Eulerian grid-point GCM. Mr. Takacs received his MS in Atmospheric Sciences from UCLA, and has 13 years of modeling experience at GSFC.

Dr. Jae-Kyung Schemm has been working on systematic forecast error analysis in numerical weather prediction and on general circulation model diagnostics. Dr. Schemm has 6 years of experience at GSFC. She received her PhD in Meteorology from the University of Maryland.

THE RELATIVE INFLUENCE OF LAND AND OCEAN PROCESSES ON PRECIPITATION VARIABILITY

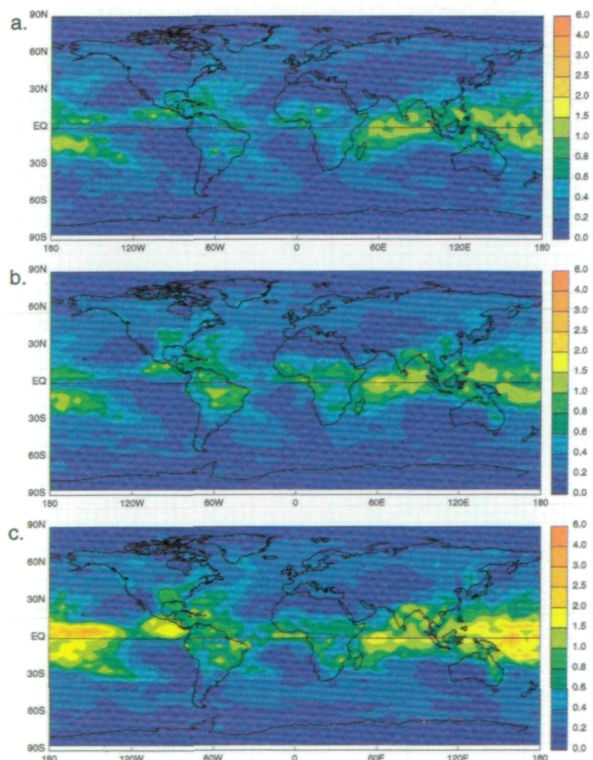
THE RELATIVE degrees to which land surface and ocean processes define climate variability have been the subject of much debate. In explaining hydrological persistence over land (as manifested by extended droughts or rainy periods), for example, some researchers stress the importance of concurrent SST anomalies, whereas others focus mostly on land-surface feedbacks. Quantifying the land's influence on variability is important, in part because land-surface characteristics are affected by human activity.

Coupled models of the Earth system provide a unique framework for addressing the problem—in the modeling environment, we can disable at will the influence of land or ocean processes on the simulated climate variability. We have designed a series of such numerical experiments using ARIES, an atmospheric GCM developed at NASA/GSFC, coupled to a sophisticated land-surface model that includes explicit vegetation control over the surface energy balance.

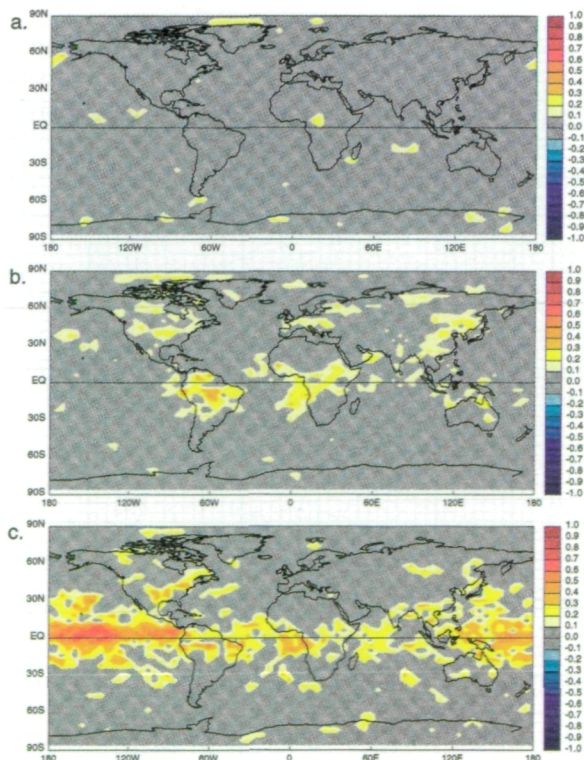
Each of the following three experiments was integrated for at least 10 years:

- Experiment 1. The atmosphere is forced by climatological mean SSTs and by the climatological mean behavior of the land surface.
- Experiment 2. The fully interactive atmosphere/land system is forced by climatological mean SSTs.
- Experiment 3. The fully interactive atmosphere/land system is forced by time-varying SSTs taken from observational datasets.

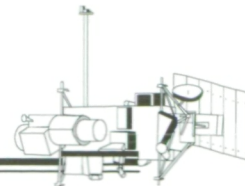
Thus, the influence of land and ocean variability on precipitation variability is disabled in Experiment 1, the land's influence is enabled in Experiment 2, and the ocean's influence is added in Experiment 3. The prescribed climatological means do vary seasonally; however, they contain no diurnal, synoptic-scale, or interannual variations.



Standard deviation of annual precipitation (mm/day) for (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3.



One-month lagged autocorrelation of precipitation for (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3.



Here we characterize simulated precipitation variability by the standard deviations of annual precipitation and by the 1-month-lagged autocorrelations of precipitation, shown in the first and second figures, respectively. The autocorrelations serve as measures of hydrological persistence. These figures, and the associated statistical analyses, suggest that land-surface processes are responsible for much (one-half or more) of the variability and persistence in mid-latitude and tropical precipitation over land.

The accuracy of these results, of course, is limited by potential deficiencies in the component models. It depends on the ability of the coupled models to reproduce the observed variability realistically and, for example, to capture the proper teleconnections between tropical SSTs and mid-latitude precipitation. An evaluation is currently underway. Preliminary comparisons of the simulated standard deviations with those derived from gridded observational precipitation data are very encouraging.

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Dr. Randal Koster, a GSFC employee for 6 years, works in the Hydrological Sciences Branch of the Laboratory for Hydrospheric Processes and contributes to GSFC's Coupled Climate Dynamics Office. His studies focus on land-surface modeling and water-vapor transport in GCMs. He received a BS from the California Institute of Technology, and an MS and a PhD from the Massachusetts Institute of Technology.

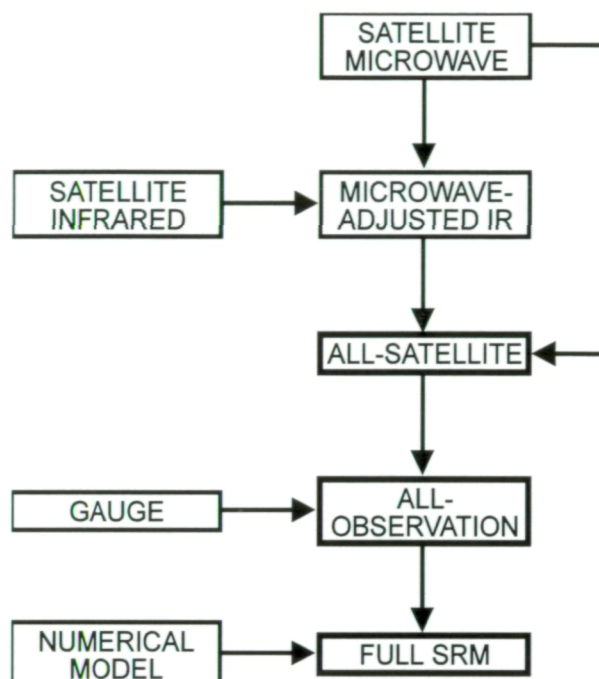
Dr. Max Suarez, a GSFC employee for 10 years, works in the Climate and Radiation Branch of the Laboratory for Atmospheres and contributes to GSFC's Coupled Climate Dynamics Office. His main interests are climate modeling and studies of the atmospheric circulation. He holds a BS from the University of Florida, and a PhD from Princeton University.

FINDING THE "BEST" GLOBAL PRECIPITATION ESTIMATE

HOW MUCH PRECIPITATION fell over the entire globe last month? No single method exists for reliably estimating this number, needed to fully understand the pivotal role that rain and snow play in the global hydrological cycle, in human activities, and in the biosphere generally. Scientists are searching for new objective techniques that will combine the useful portions of the available global estimates, and downplay areas where problems are believed to exist.

Satellite microwave channels provide a relatively good physical connection between the signal observed and precipitation-sized hydrometeors (rain drops, snow flakes, and small hail). However, such estimates are inadequate when the underlying surface is cold or when precipitation results from shallow clouds. In addition, microwave sensors cannot be made compact enough to provide useful resolution from geosynchronous orbit, so microwave estimates are only available a few times a day from polar-orbiting platforms. Satellite infrared channels provide a poorer physical connection to precipitation, but they are available from geosynchronous satellites, permitting nearly continuous sampling in time. Raingauges suffer a different sampling problem; they are point measurements of a very noisy field, and they are largely unavailable in oceanic and underdeveloped regions. On the whole, gauges underreport precipitation in windy conditions, but, more generally, the bewildering variety of raingauges in use displays widely varying error characteristics. Finally, numerical weather-prediction models provide complete global coverage, using the governing physical laws and observed initial conditions. The greatest shortcomings include approximations in solving the equations and errors in starting the model run because of incomplete observations. More subtly, the production of precipitation is related to many other physical processes, so errors in seemingly unrelated parts of the model can manifest themselves in the precipitation forecast. We do not consider weather radars, because they do not provide enough quantitative coverage to be useful on a global basis.

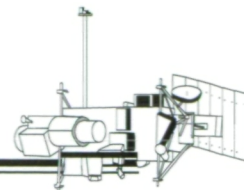
The new satellite-raingauge-model (SRM) technique, shown schematically in the first figure, combines precipitation estimates from all of these sources, objectively favoring the estimate with the highest confidence. First, we recognize that infrared precipitation estimates typically are too large, particularly in higher latitudes, where cold



Schematic diagram of the satellite-raingauge-model technique.

cirrus clouds in the vicinity of fronts and jet streams are not necessarily indicative of heavy precipitation. Consequently, infrared estimates cannot be used in the weighting method described below, which assumes unbiased input fields. Rather, we use the microwave estimates to adjust the infrared toward the (usually small) biases in microwave estimates. Where the infrared are completely unreliable (outside 40°N to 40°S), the "all-satellite" estimate is just the microwave estimate alone.

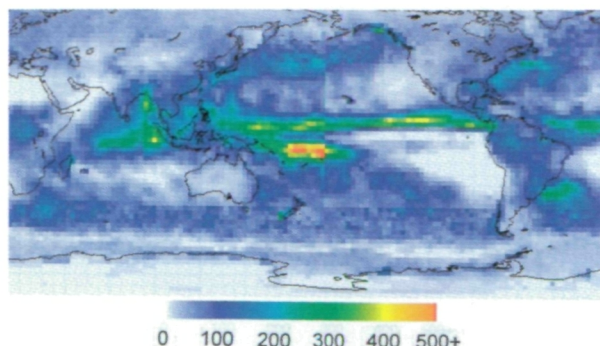
The all-satellite field is combined with an analysis of raingauge totals to form an "all-observation" field, that is then combined with accumulations from model forecasts to produce the full SRM estimate. These combinations are done by weighting each input field by its inverse relative variance (a measure of certainty for that input). This sequential combination approach will allow us to examine the impact of each new field, and allow other researchers to specify which product they would like to use in their own research. For example, numerical modelers probably wish to compare their results against the all-observation field, rather than the full SRM estimate. Fortu-



nately, the full SRM estimates are unaffected by the order of combination in the last two steps. Taken together, the sequential combination is exactly equivalent to simultaneously combining all three fields, as long as inverse relative variance weighting is used.

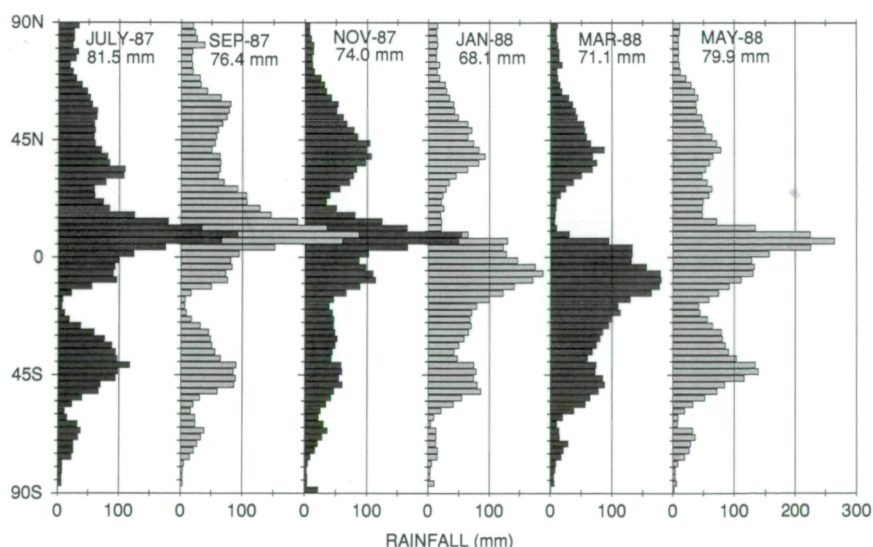
Further research is needed to estimate accurately the variance of the individual precipitation fields. At present, we simply approximate the satellite and raingauge variances by the portion introduced by sampling (in space and time). Also, we presently assign a high variance to the numerical model field, so that it is reduced to filling in blanks in the all-observation field.

The full SRM estimate for August 1987 (the second figure) shows many of the qualitative features we expect, including the Inter-Tropical Convergence Zone (ITCZ; the band of precipitation roughly following the Equator), dryness in subtropical latitudes, and enhanced precipitation in the mid-latitudes. Broad regions of the image, particularly over oceans, are identical to the all-satellite estimate because of the lack of gauge data. In these regions, the relatively smooth central portion of the image (40°N to 40°S) is the result of the microwave-adjusted infrared estimate, while the higher latitude portions of the image reflect the (noisier) microwave estimate. Conversely, the gauges fill in holes in the satellite data, such as high-latitude areas in the Americas, southern Greenland,



Full satellite-raingauge-model precipitation estimate (in mm) for August 1987.

and scattered sites in polar regions. The gauge analysis also dominates in western Europe, the eastern U.S., and much of Australia because these regions have sufficiently dense networks of raingauges. The polar regions are almost entirely filled from numerical model accumulations. The model values inserted in the Arctic match the surrounding all-observation values fairly well, but there is an obvious discontinuity around the Antarctic. A quick review of data availability shows that this discontinuity reflects disagreement between the microwave estimate (to the north) and the model accumulations (to the south), perhaps reflecting deficiencies in the microwave algorithm. Despite the uncertainty such a discontinuity raises,



Full satellite-raingauge-model precipitation estimate (in mm), averaged over 2.5° latitude bands for odd-number months in the period July 1987 to June 1988. The value at the top of each graph is the corresponding global average.

we proceed with computing global averages, both because the latitudes higher than 60° only contain 13 percent of the Earth's surface area, and because the precipitation averages there are small.

A more compact summary of the SRM results is provided by computing averages over 2.5° latitude bands for alternate months over the 12 months of July 1987 to June 1988 (the third figure). The most striking feature is the shift from a strong ITCZ maximum slightly north of the Equator in Northern Hemisphere summer to a lower, broader maximum slightly south of the Equator in the opposite season. This behavior corresponds to the results that we expect from previous long-term studies based on gauges alone, but shows important quantitative differences. At about 70°S, the profiles jump up to the model values because that is where model fill-in begins to dominate the SRM technique.

The SRM technique provides an objective means of combining independent precipitation estimates without having detailed knowledge of the statistical behavior of the individual estimates. Although validation is extremely difficult, since all data sources are included almost by definition, the SRM technique is clearly functioning as intended (i.e., at each stage the better estimate gets more

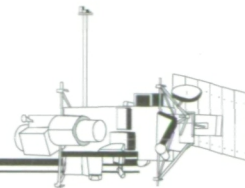
weight and the estimated error of the combination is no greater than the error of the better estimate). Comparisons with the individual fields and independent studies indicate that the SRM is reasonable, but that further work must be done to understand the characteristics of the individual fields contributing to the SRM. Also, the relative error estimates must be improved to account for all sources of error, not just sampling. As these improvements are made, the SRM methodology should permit a clearer picture of the actual precipitation pattern, allowing a more accurate perspective on our planet's atmosphere.

This work was done in collaboration with Dr. George Huffman, a Senior Staff Scientist with Science Systems and Applications, Inc.

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Sponsor: Office of Mission to Planet Earth

Dr. Robert Adler is Head of the Mesoscale Dynamics and Precipitation Branch of the Laboratory for Atmospheres. His research interests focus on the use of satellites for remotely determining precipitation on a variety of time and space scales around the globe. He holds a PhD in Atmospheric Science from Colorado State University.



POSSIBLE SOLAR INFLUENCES ON CLIMATIC CHANGE

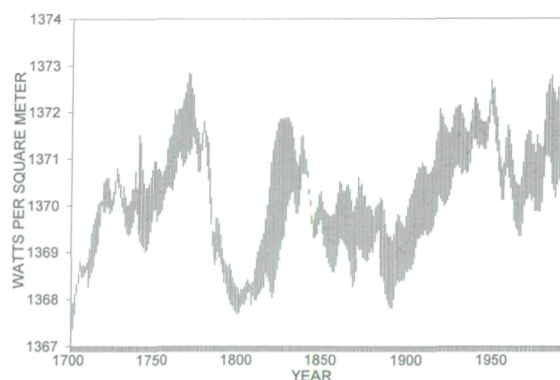
IN THE LAST 15 YEARS, satellite measurements have confirmed that the light output of the Sun varies. Although many of the short-term variations—lasting from days to weeks—can be successfully modelled using sunspot blocking and facular emission, on the time scale of months to years, there may be as-yet-undetected additional changes. The longer the time scale of the variations, the deeper the likely source for the perturbation will be. Relatively short variations (day to months) are caused by sunspots and faculae which are perturbations in the top few thousand kilometers of the Sun. The root source of the longer variations (decades to centuries) may arise from deep within the convection zone, perhaps at its base or just below its base. These changes could result from stochastic variations in the energy transport arising from the finite number of convective cells involved, or from changes in pressure, perhaps arising from changes in the strength of the magnetic field, which alter the rate of energy transport. Plausible arguments can be made in behalf of both mechanisms. Such changes presently fall outside the domain of usual theories of stellar structure.

Since the turn of the century, some scientists have advocated that there are long-term variations in solar brightness that are not closely correlated with the 11-year solar activity cycle. Suggested proxy indices for these solar luminosity variations include sunspot structure, equatorial solar rotation rate, solar cycle length, the decay rate of sunspots, the fraction of sunspots having only penumbrae, the solar diameter, the mean level of solar activity, the equivalent width of photospheric Fraunhofer lines, and the bisectors of these absorption lines. Although not all these solar indices are measured at all times during the last century, those that have been measured for a 100 years or longer all have remarkably similar temporal variations.

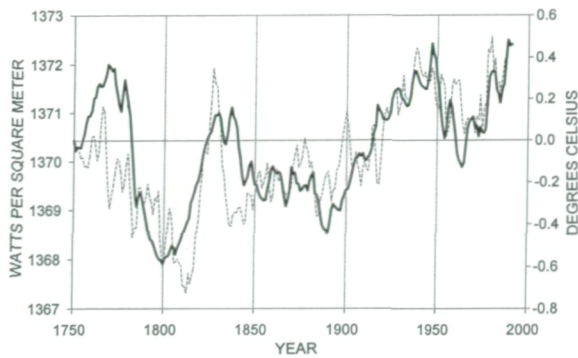
It is not merely fortuitous that these similarities exist. For example, changes in both sunspot structure and in the number of penumbral sunspots can be related mathematically to changes in the decay rates of sunspots. In all theories for the destruction of sunspots, their rate of decay is proportional to a solar convective velocity. Changes in convective velocities would imply a change in energy transport within the Sun, which, in turn, would be accompanied by a change in the brightness of the Sun. Thus, it is plausible that changes in these indices are telling us that the Sun is a variable star on the time scale of decades

to centuries. Five of these indices were used to construct a model for the solar irradiance variations seen since 1700 (first figure). The longer term variations are postulated to be a few tenths of a percent, or only slightly more than the variations seen in the last 14 years. The Sun may not only be very active in the last few decades, but it may also be brighter than it has been at any time in the last two centuries.

Should such solar brightness variations be occurring, they would affect the temperature of the Earth. In fact, Earth temperatures and the solar irradiance model do correlate with each other, as can be seen from the second figure. In this view of the Earth-Sun system, we are viewing the Earth as a radiometer which is responding to solar variations. Of course, the Earth's climate is also responding to volcanic eruptions, changes in oceanic circulation, increases in greenhouse gases, and other perturbations, but this model for the solar irradiance variations suggest that more than 50 percent of the past long-term variability in climate was caused by solar variations. Confirmation or refutation of this hypothesis will only come from continuous, multi-decadal, high-precision satellite measurements of the solar total irradiance.



A plot showing the combined solar irradiance model. The error bars show the relative disagreement among the different techniques used to derive the irradiance variations. For 1700 through 1874, models based upon cycle length, cycle decay rate, and mean level of solar activity are used. For 1875 through 1992, up to five solar indices are used.



The annual mean Northern Hemisphere temperature variations from Groverman and Landsberg for 1700 through 1879, and from Hansen and Lebedeff (1988) for 1880 to present, after being smoothed by an 11-year running mean (dotted line). The model irradiances are overlain to show their similarity.

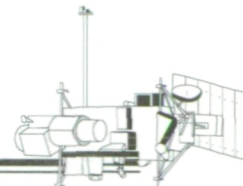
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Sponsor: Office of Space Science

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Mr. Douglas Hoyt earned degrees in physics and astronomy at Rensselaer Polytechnic Institute and the University of Colorado. He is Senior Scientist at Research and Data Systems Corporation. His research interests include problems in solar physics, radiometry, and climatology.



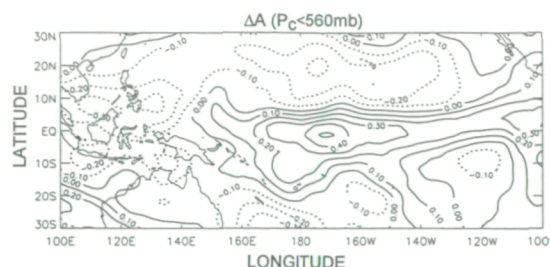
HYDROLOGY/CRYOLOGY

COOLNESS IN THE TROPICAL PACIFIC DURING AN EL NIÑO EPISODE

ATMOSPHERIC WATER VAPOR and clouds are two of the most important elements affecting the Earth's climate. As climate changes—either due to human activities or natural variations—atmospheric water vapor and clouds vary accordingly, which perturb the Earth's radiation balance and further alter the climate. About every 2 to 5 years, the precipitation and SST have been found to be exceptionally high in the central and eastern equatorial Pacific, with the reverse condition occurring in the western equatorial Pacific. This phenomenon is called El Niño, (The Boy Child) since it occurs around Christmastime.

We investigated the response of radiation budgets to changes in clouds and the atmospheric water vapor in an El Niño episode by using the SST data from the National Meteorological Center (NMC), satellite-derived cloud data from International Satellite Cloud Climatology Project (ISCCP), and the Earth radiation budget data from the Earth Radiation Budget Experiment (ERBE) for the tropical Pacific (100°E to 100°W, 30°S to 30°N). Analyses were performed for April 1985 and April 1987. The former is a non-El Niño year; the latter is an El Niño year.

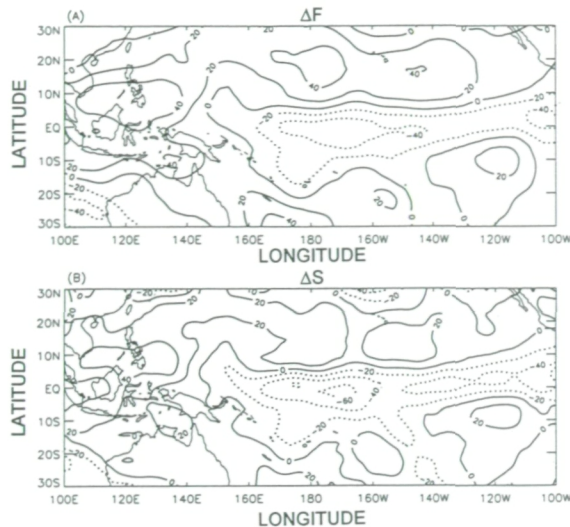
The 1987 El Niño became evident by the end of 1986, and persisted through most of 1987. Compared to April 1985, the SST over the central and eastern equatorial Pacific in April 1987 was 2.0 °C higher. The corresponding change in the high-level fractional cloud cover with cloud-top pressure less than 560 mb is shown in the first figure. Compared to April 1985, the high-level fractional cloud cover in April 1987 increased in the central and eastern equatorial Pacific, but decreased in the tropical and western equatorial Pacific regions. A large positive change (April 1987 minus April 1985), exceeding 0.3, was found in the central and eastern equatorial Pacific, while a large negative change of -0.3 was found in the western equatorial Pacific, indicating an eastward shift of the convection center by 60° longitude. A negative change of -0.2 covered a large portion of the Northern Hemispheric tropical region. It is evident that the high-level cloud increased in the equatorial region but decreased in the Northern Hemispheric tropical region in April 1987. These changes imply a strengthened Hadley circulation (a direct, thermally driven, and zonally symmetric circulation) in the Northern Hemispheric Pacific region. The high-level clouds remained nearly unchanged in the Southern Hemi-



Difference (April 1987 minus April 1985) in the fractional covers of high clouds with the cloud-top pressure < 560 mb.

spheric tropical Pacific. Averaged over the equatorial and tropical Pacific (30°S-30°N), there was almost no change in the high-level cloud cover.

Corresponding to the changes in the SST and cloudiness, the outgoing longwave radiation (OLR) and the net downward solar radiation at the top of the atmosphere (TOA) also showed significant change. Changes in the radiation budgets at TOA are caused primarily by clouds, humidity, and atmospheric and surface temperatures. Water vapor reduces the OLR but enhances the absorption of solar radiation. Both processes have a warming effect on climate and are especially important in clear-sky conditions. On the other hand, clouds reflect solar radiation to space and shield longwave radiation from loss to space. The former has a cooling effect, but the latter has a warming effect. The net effect of clouds on climate could be either warming or cooling depending upon space, time, and cloud types. Changes in the OLR (ΔF) and the net downward solar radiation (ΔS) at TOA are shown in the second figure. In the central and eastern equatorial Pacific, there are more high-level clouds in April 1987 than in April 1985. As a result, both the OLR and the net downward solar radiation decrease in April 1985 (negative values of ΔF and ΔS). The opposite situation was found in most of the tropical Pacific. The change in the OLR reached 50 W/m² in the equatorial region and 40 W/m² in the tropical Pacific, which is equivalent to a change of 13 °C and 10 °C in the brightness temperature, respectively. These changes in the OLR were largely compensated by changes in solar radiation, so the change in the total radiation at TOA was generally smaller than 10 W/m². The negative change in the total radiation covered most of the tropical Pacific.



Differences (April 1987 minus April 1985) in the outgoing longwave radiation (A) and the net downward solar radiation (B) at the top of the atmosphere.

Changes in the OLR and the net downward solar radiation at TOA were negatively correlated with the high-level cloud cover.

Averaged over the entire equatorial and tropical Pacific, the Earth-atmosphere system received less radiative energy by 3.5 W/m^2 in the warmer month of April 1987 than in the month of April 1985, which was caused pri-

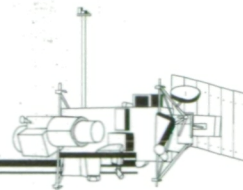
marily by a drier Northern Hemispheric tropical Pacific in April 1987. Because of the decrease in water vapor, the emission of longwave radiation to space increased by 1.3 W/m^2 , and the absorption of solar radiation decreased by 1.1 W/m^2 . Thus, the warming of the Earth-atmosphere system due to water vapor was 2.4 W/m^2 smaller in April 1987 than in April 1985. The change in cloud radiative forcing was large in both the infrared and solar radiation, but the net was only 0.8 W/m^2 due to cancellation. This indicates that changes in cloudiness caused a slight warming in this region in April 1987.

This study supports Lindzen's hypothesis that reduced water vapor in the vicinity of the enhanced convection region produces cooling which counteracts warming in the tropics. Clouds have strong effects on both infrared and solar radiation, but the net effect on the radiation budget at the TOA changed only slightly between April 1985 and April 1987.

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MAPPING OF THE GREENLAND ICE SHEET: A CONTRIBUTION TO GLOBAL CLIMATE MONITORING

MORE THAN 70 percent of the world's fresh water exists as perennial ice. Most of this ice is contained in the large polar ice sheets in Antarctica and Greenland, which are fed by snow and depleted by either calving icebergs or meltwater. The net gain or loss of ice determines whether the ice sheets grow or shrink, and causes an equivalent change in sea level. Particular concern about the mass balance of the ice sheets in the context of recent and projected global warming is focused on the Greenland ice sheet. This ice sheet already experiences a great deal of melt, and has the capacity to raise sea level by 5 meters, were it all to melt. In contrast, the much larger Antarctic ice sheet is too cold to experience substantially increased melt for even dramatic increases in atmospheric temperature. The combined contribution to sea level of all smaller ice caps and all mountain glaciers is an order of magnitude less than the potential contribution from the Greenland ice sheet.

On the Greenland ice sheet, the processes of snow accumulation and melting interact to create a succession of distinct snow facies (or zones) that are helpful in monitoring the regional climate. These zones differ in their subsurface structure, snow-grain size, and free-water content. Remote sensors operating in the microwave portion of the electromagnetic spectrum are particularly sensitive to these differences. In particular, the synthetic aperture radar (SAR) can provide images of the ice sheet that easily discriminate these facies. For this reason, and because of the additional benefits of radar in penetrating clouds and operating in the extended polar night, SAR is the instrument of choice for monitoring the climate effects of the Greenland ice sheet.

Since 1978, various SARs have provided glimpses of the ice sheet, but not until the ERS-1 satellite (launched in 1991) has nearly complete coverage of the ice sheet been possible. This research project makes use of data from the ERS-1 SAR to address three specific objectives:

- To mosaic the ice sheet and identify the positions of the different snow facies to serve as a baseline for identifying future, climatically driven shifts in their positions;
- To study the temporal behavior of the backscatter from each facies over an annual cycle; and,
- To compare the position of the ice sheet margin with earlier maps to search for systematic changes in mar-

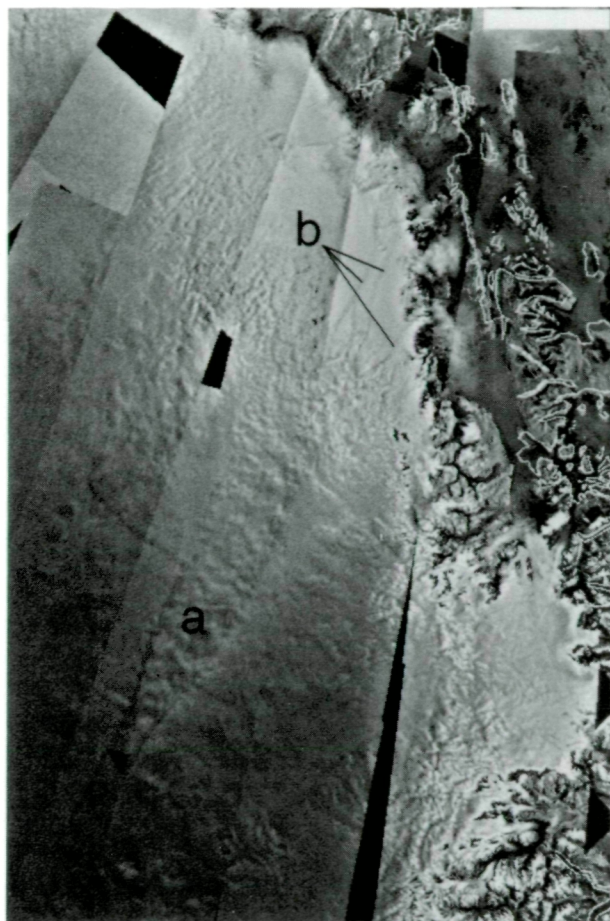
gin position that might point to climatic responses of the ice sheet.

Nearly 400 100-km x 100-km scenes of Greenland were collected by the ERS-1 SAR during a 35-day period in August and September 1992. These data were used to create the mosaic shown in the first figure, which clearly shows the different snow facies. The interior of the ice sheet is occupied by dry-snow facies. Nearer the coast, we find percolation facies. Continuing toward the coast, wet-snow facies, lakes, and streams are formed. Bare-ice facies extend to the margin of the ice sheet.

The original data have a ground resolution of 25 m, but to display such a large area as presented in the first figure, the data were averaged to a resolution of 1 km. The full-resolution data have permitted a number of other discoveries. Among them:

- In the apparently featureless dry-snow facies, structures can be seen in fully enhanced imagery. These are probably direct or indirect indications of surface topography.
- The positions of the facies, while correlated closely with elevation, exhibit significant variations in some locations. These are likely the result of local meteorological effects such as preferred storm tracks and areas of strong katabatic (drainage; directed down the slope of an incline) winds.
- There is a large, previously undiscovered drainage feature dominating northeast Greenland, as shown in the second figure. This feature feeds Zachary Ice Stream and is remarkably similar in appearance to West Antarctic ice streams, although no marginal crevasses could be resolved in the SAR imagery in the upper two-thirds of the feature.

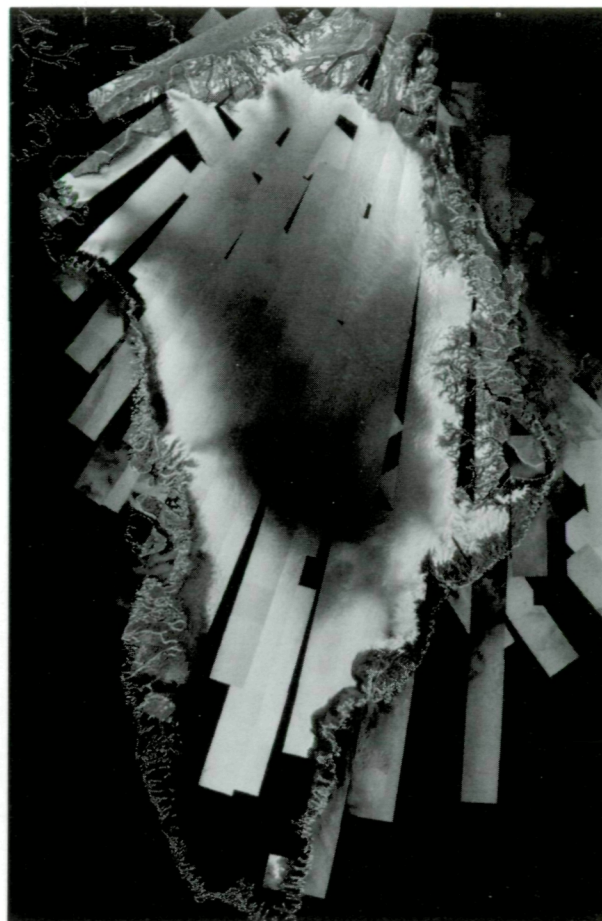
The temporal study is based on the acquisition, every 35 days, of a single 100-km-wide swath of data extending from the center of the ice sheet to the southwestern margin. The series begins in August 1992 and extends to April 1993. Thus, the freeze-up process is included, but not yet the onset of summer melt. As expected, the freeze-up has little effect in the dry-snow and percolation facies, but does cause a major change in the wet-snow facies as the free water is refrozen and lakes freeze. This temporal sequence will improve the ability to identify the areal extent of the different facies.



Mosaicked SAR imagery of northeast Greenland showing large flow feature (a) which drains ice toward the coast. (b) points to streamers of crevasses formed as the rate of ice flow increases. Scale bar is 100 km long. (SAR imagery © ESA 1991, 1992.)

Temporal coverage also has permitted the measurement of ice velocity on Jakobshavns Glacier. This glacier moves extremely rapidly (almost 20 m/day at its terminus). Many features identified on two images separated in time by only 105 days were used to measure velocities ranging from 400 to 2,000 m/year in a region 20 to 50 km upstream of the terminus. This represents the first time that measurements of ice-flow velocity have been made with SAR data. The results compare well with velocities obtained independently by H. Brecher using traditional aerial photogrammetric techniques.

Future work will include generation of a second ice-sheet mosaic using winter imagery. The temporal studies will be extended to a full annual cycle, and low-Sun-angle,



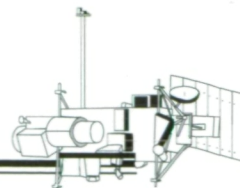
ERS-1 SAR mosaic of Greenland acquired between August 1 and September 1, 1992. The brightness indicates the amount of energy scattered back to the satellite. Brightness patterns reveal the snowpack character, delimiting the boundaries of the snow facies defined by Benson and discussed in the text. (SAR imagery © ESA 1991, 1992.)

high-resolution, visible imagery will be examined to determine the correlation of surface topography and subtle SAR features in the dry-snow zone. The margin of the ice sheet will also be compared with older maps.

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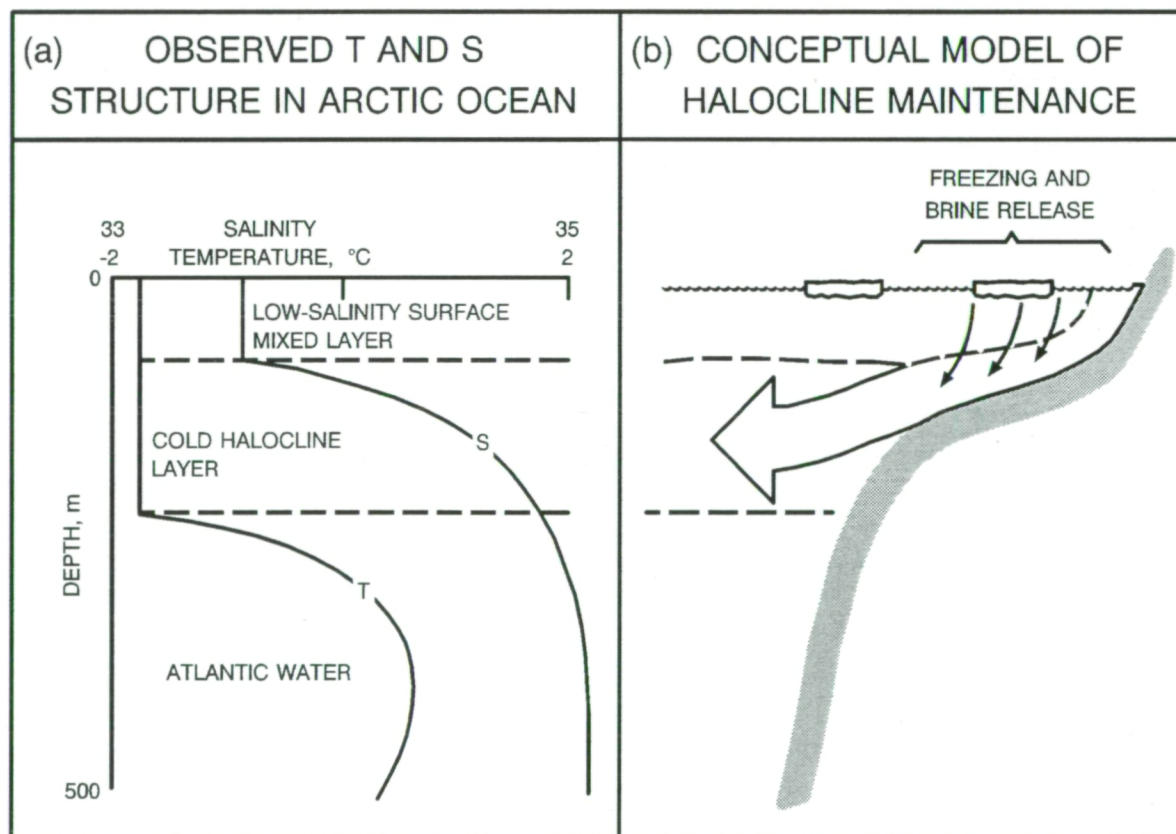


THE CONTRIBUTION OF ALASKAN, SIBERIAN, AND CANADIAN COASTAL POLYNYAS TO THE COLD HALOCLINE LAYER OF THE ARCTIC OCEAN

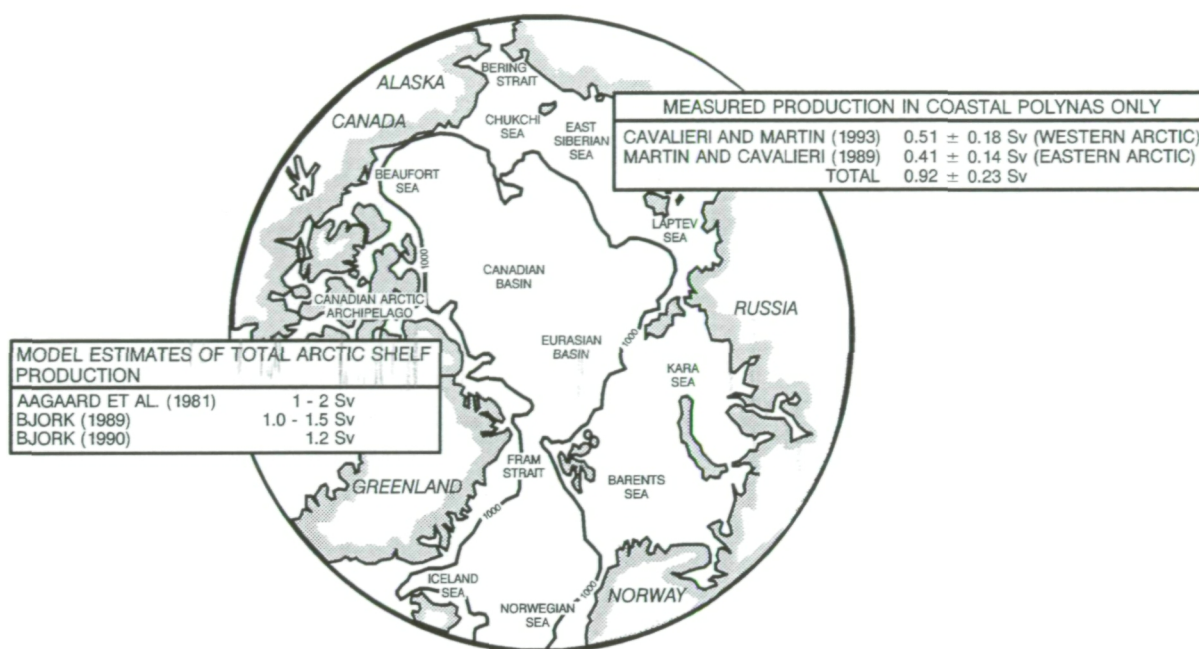
THE UPPER LAYER of the Arctic Ocean is characterized by a strong density gradient produced by an increase in salinity downward from the surface. A schematic illustration of the temperature and salinity structure of this upper layer is shown in the first figure, top panel. This salinity gradient, called the *halocline*, produces a very stable layer and serves to insulate the surface ice cover from the heat stored by the underlying warm Atlantic water. Depletion of this protective layer would result in the loss of the perennial Arctic sea-ice cover, which, in turn, would have a profound effect on the global climate system. Understanding the maintenance of this layer is one of the important problems of Arctic science.

Several Arctic Ocean circulation and geochemical studies suggest that this cold halocline layer is maintained by

the advection of cold, saline water masses produced during sea-ice growth on the continental shelves surrounding the Arctic basin. Coastal polynyas (non-linear openings in the sea-ice cover, often found adjacent to coasts) on the Alaskan, Siberian, and Canadian continental shelves, in particular, have been cited as important sources of this dense water. Coastal polynyas are usually kept open by offshore winds. A schematic illustration of the maintenance of the halocline by coastal polynyas is given in the first figure, bottom panel. The goal of this research is to determine quantitatively the amount of dense water produced by these coastal polynyas. The results of this study will serve to test the hypothesis that these polynyas are the source of dense water that maintains the cold halocline layer of the Arctic Ocean.



Schematic illustration of the temperature and salinity structure of the upper Arctic Ocean (a) and the maintenance of the halocline by coastal polynyas (b) (from Aagaard et al., 1981).



The Arctic Ocean and peripheral seas. The shelf region is defined by the 1,000-m isobath (solid line). Estimates of dense water production are given from calculations based on the Nimbus-7 SMMR satellite study and from theoretical and model studies.

The first part of this research examined the production of dense water in coastal polynyas on the Kara, Barents, and Laptev Sea shelves and was completed in 1989. The second part, performed in 1993, examined coastal polynyas in the Bering, Beaufort, Chukchi, and East Siberian Seas. The results were combined with the 1989 results to obtain a total estimate of dense water production by Arctic polynyas. A map of the Arctic shelf regions and the peripheral seas is shown in the second figure. The production of dense shelf water by the coastal polynyas was calculated through the combined use of microwave radiance data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), meteorological data, and ocean surface salinity data for nine winter periods (1978 through 1986). In the eastern Arctic, recurrent polynyas occur along the coasts of the islands in the Kara, Barents, and Laptev Seas. On the western side of the Arctic, polynyas occur along the Canadian, Alaskan, and Siberian coasts. Dense water produced in the coastal polynyas of the Bering Sea flows northward through the Bering Strait and contributes to the cold halocline layer of the Arctic Ocean. For the eastern Arctic, the average dense water production is 0.41 ± 0.14 Sv (Sv = 1 Sverdrup or 10^6 cubic meters per second), while for the western

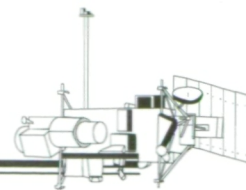
Arctic the production is 0.51 ± 0.18 Sv. The combined contribution shows that the coastal polynyas on the Arctic shelves generate about 0.7 Sv to 1.2 Sv of dense water. This range is less than the 1-2 Sv predicted by modeling and theoretical studies (the second figure) suggesting that polynyas alone generate insufficient brine to renew the halocline layer.

Future work will explore other potential sources of dense water production including the seasonal ice growth on the shallow shelf seas and the freeze-up of areas of low ice concentration resulting from the response of the ice cover to infrequent violent storms over the shelves. This study was done in collaboration with Professor Seelye Martin of the School of Oceanography, University of Washington, Seattle, WA.

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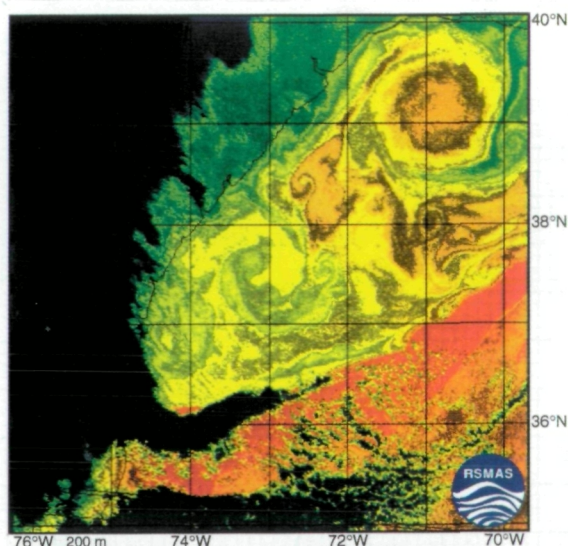
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Dr. Donald Cavalieri is a physical scientist in the Oceans and Ice Branch of the Laboratory for Hydrospheric Processes. He earned a PhD in Meteorology and Oceanography from New York University. Dr. Cavalieri has been at GSFC for 14 years.



ARE GULF STREAM WARM CORE RINGS DIPOLES?

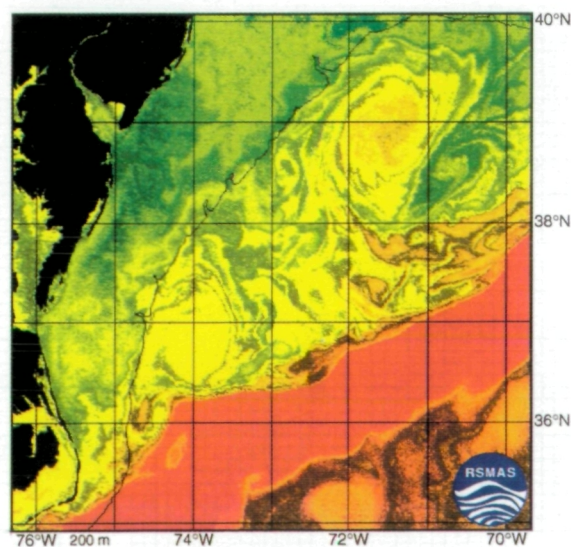
THE INTERACTION of a warm core ring (a cyclonic ocean-water phenomenon) with its environment has importance in supporting the flux of physical and biogeochemical properties from coastal margins (the most productive part of the world ocean) into the open ocean and vice versa. Arriving at well-defined flux budgets for a particular property is difficult because of the random (poorly predicted) association of vortical structures during these interactions which greatly enhance the lateral transports. The predictive capabilities for estimating the spatial and temporal contributions of these types of interactions would be much improved if the randomness of the phenomenon could be reduced. Toward that end, modeling the vortex pair as a so-called *rotating modon* has recently been constructed.



Warm core ring 82-B approximately 1 month after formation as seen in a sea-surface temperature image derived from NOAA-7 AVHRR imagery on 30 March 1982 (day 89). The blue patch dominating the western edge of the image is cloud. The continental shelf is delimited by the 200-m isobath and its overlying water is mostly green. The Gulf Stream is the warmest feature in the image and runs diagonally across the lower right corner. The ring is the large orange circular feature centered at approximately 70.8°W, 39.2°N. The cyclone is the tight green spiral centered at approximately 69.8°W, 38.8°N. Note the green streamer of shelf water being pulled between the eddies and then being wrapped clockwise around the ring.

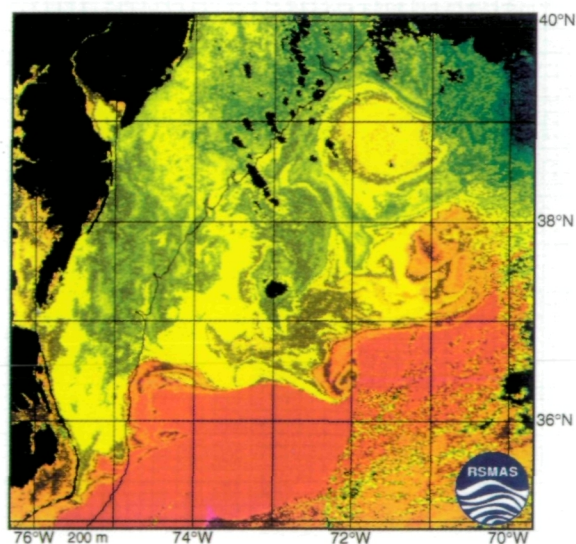
In such a model, the vortices are always paired—from formation to disintegration—and do not randomly interact. This is not in keeping with the historical description of such warm core rings, which portrays them as isolated monopoles that occasionally entrain and then loose smaller scale cyclones during frontal or topographic interactions. To test the applicability of the model, warm core ring 82-B, which detached from the Gulf Stream in February of 1982, was selected for reanalysis. The ring was studied extensively during the Warm Core Rings Experiment, so an extensive archive of *in situ* and remotely sensed data were available.

The first figure (left) shows 82-B on March 30, 1982 (day 89), approximately 1 month after formation. The image is centered off the East Coast of the U.S. near the Chesapeake Bay. The blue-green-yellow-orange-red false-color sequence represents temperature changes of approximately 5, 10, 20, 25, and 30 °C, respectively. The ring appears as



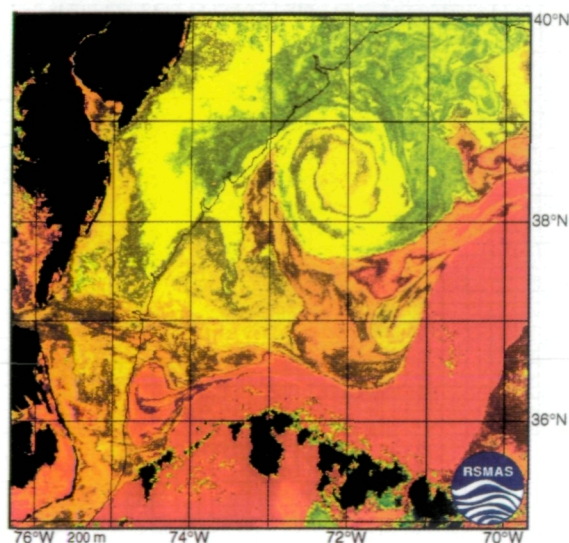
Warm core ring 82-B as seen on 24 April 1982 (day 114), a little more than 3 weeks after the first figure. The ring is the large yellow and (slightly) orange D-shaped eddy centered at approximately 71.6°W, 38.9°N. Once again, a smaller companion cyclone is found to the southeast of the ring centered at approximately 70.7°W, 38.6°N. The cyclone in this image appears more intense or well developed than the one in the first figure, with apparently more shelf water being advected around the periphery of the ring.

a warm circular feature near a colder and smaller cyclone, the mutual interaction of which pumps a streamer of shelf-water between the eddies and into the ring's circulation field. The second figure (previous page—right) shows 82-B on April 24 (day 114). The ring is D-shaped and, once again, found next to a smaller cyclone. The third figure (left) shows 82-B on May 5 (day 125). In this image, the companion cyclone has been pulled into a long filament that wraps around the western and southwestern part of the ring. Note how the filament joins the shelf water streamer in the southeastern quadrant of the ring's circulation field. The fourth figure (right) shows 82-B on May 18 (day 138) and demonstrates the robustness of the dipole configuration, since it is present during a Gulf Stream encounter—the most energetic interaction a ring can undergo. The presence of cyclones around the periphery of warm core rings is seen in the top left, top right, and bottom right figures, and the strong deformation they can undergo is clear in the third figure (left). The question remains whether the cyclones are permanent features of rings or simply eddies that are captured during stochastic encounters.

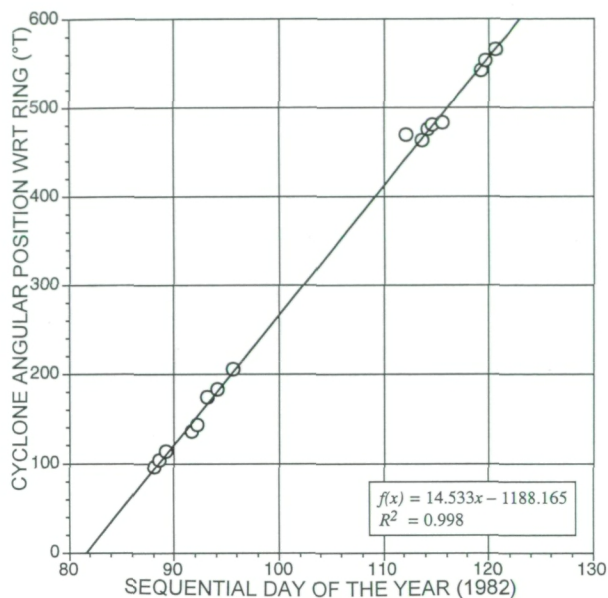
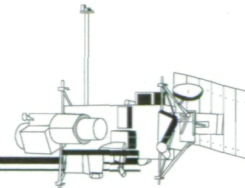


Warm core ring 82-B as seen on 5 May 1982 (day 125), approximately 11 days after the second figure. The ring is the large yellow (deformed) circular eddy centered at approximately 71.6°W, 38.7°N. In this image, the companion cyclone has been pulled into a long filament that wraps around the western and southwestern part of the ring. Note how the filament joins the shelf-water streamer in the southeastern quadrant of the ring's circulation field.

The simplest way to test the applicability of the dipole model to ring behavior is to estimate the positions of the centers of the eddies as a function of time in a non-translating reference frame (i.e., in a coordinate system in which the velocity vector of the ring has been removed), and then determine if the cyclone rotates around the anticyclone at a constant rate for a long period of time. If this is done, the evolution of the cyclone is naturally described by r , the distance between the center of the cyclone and the center of the ring, and θ , the angle the line makes between the centers with respect to due North. The fifth figure is a plot of θ over a 40-day period when 82-B was isolated from the direct influence of the Gulf Stream; before and after this period, the ring was interacting with the Gulf Stream. The slope of the fitted line indicates a rotation rate of the cyclone around the ring of $\sim 14.5^\circ$ per day, giving a rotation period of almost 25 days. If the rotating modon model is applicable, the angular rotation rate of the cyclone around the anticyclone should be a constant. This was found to be the case. The process should repeat without interruption, which it apparently does, even up to and including a Gulf Stream interaction. The sepa-



Warm core ring 82-B as seen on 18 May 1982 (day 138), approximately 24 days after the second figure. The ring is the large yellow circular eddy centered at approximately 72.1°W, 38.4°N. A companion cyclonic eddy is located at 70.9°W, 38.4°N. Note the proximity of the dipole to the Gulf Stream and one streamer of (red and orange) Gulf Stream fluid being pulled around the dipole all the way up its western side and another one being pulled up the eastern side of the cyclone.



The angular position of the cyclonic eddy with respect to the ring as a function of time.

ration of the data into two groups is not due to the presence of clouds but rather to a reflection of the cycle of axisymmetrization to filamentation and then back to axisymmetrization. When the cyclone is sheared out into a long filament or streamer, it is very difficult to define a center of the feature, so no center estimates were attempted under these conditions.

The primary conclusion of this initial investigation is that warm core rings spend much of their time as dipoles, not as monopoles. This is not due to episodic interactions which produce a cyclone that is captured and then lost, but rather because rings are fundamentally dipoles. This research could not have been done without satellite imagery; the time series used to produce this new result could not have been collected with *in situ* sampling alone. Of course, the *in situ* data were critical, since they were used to validate the remotely sensed data with ground-truth data.

This work was the result of an ongoing collaboration of several individuals. Dr. Richard Mied of the Naval Research Laboratory (NRL), and Dr. Denny Kirwan of Old Dominion University (ODU) were responsible for the rotating modon model, and Mr. James Brown of the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS) implemented the image processing software which was developed at RSMAS under the direction of Drs. Robert Evans and Otis Brown.

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ATMOSPHERES

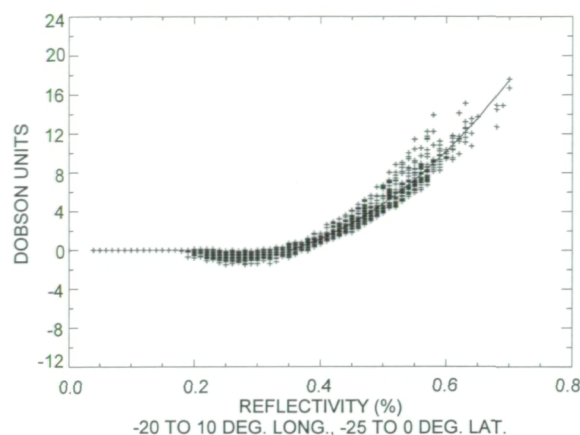
DEVELOPMENT OF MODIFIED TOTAL OZONE MAPPING SPECTROMETER O_3 ALGORITHMS FOR MARINE STRATOCUMULUS REGIONS

THE IMPORTANCE of stratospheric O_3 as a shield of ultraviolet radiation is well known. In contrast, increasing concentrations of tropospheric O_3 are viewed as potentially harmful because in the upper troposphere, O_3 acts as a greenhouse gas and near the surface, high levels of O_3 are damaging to plants and animals.

Presently there are difficulties with Total Ozone Mapping Spectrometer (TOMS) total O_3 measurements in cloudy regions, especially when the data are used to study tropospheric O_3 . Specifically, the use of a climatological cloud height in the TOMS algorithm leads to an overestimate of total O_3 in the vicinity of marine stratocumulus. Worldwide, there are four major regions of marine stratocumulus: the Eastern Atlantic off Angola, the Azores, the Eastern Pacific off California, and the off-Peru upwelling region.

The TOMS O_3 overestimate can be seen in any of these regions by comparing total O_3 from the Nimbus 7/Solar Backscatter Ultraviolet (SBUV) instrument, calculated assuming climatological cloud height, with total O_3 calculated using actual cloud heights determined by the Temperature-Humidity Infrared Radiometer (THIR) (operational from 1979 to 1984). The difference between the two is a function of reflectivity, approaching 20 Dobson Units (DU) for a reflectivity over 60 percent (the first figure). This relationship can be quantified, and TOMS reflectivity can be used with the standard gridded TOMS total O_3 product to obtain a corrected TOMS total O_3 for regions of persistent marine stratocumulus.

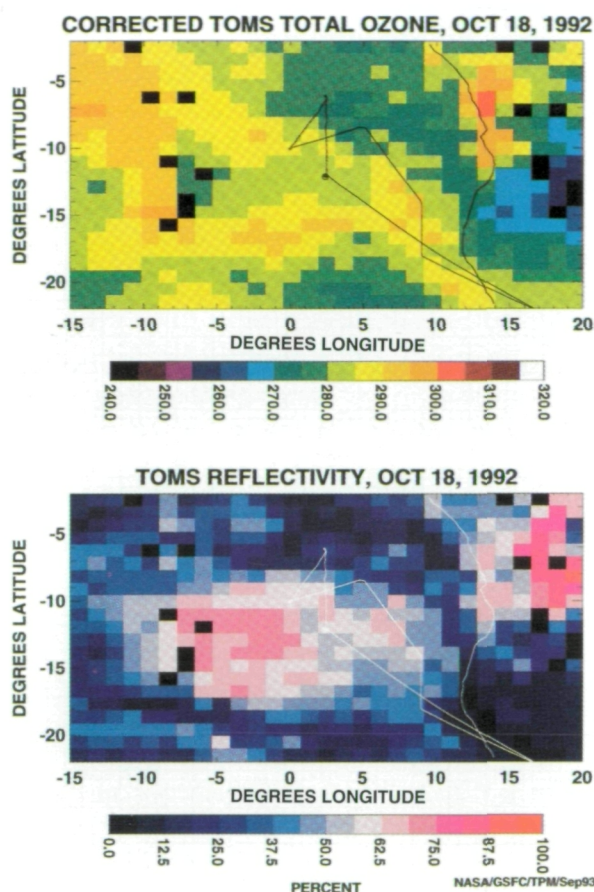
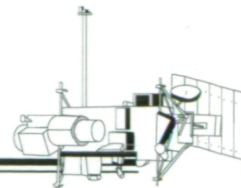
The method was used to correct real-time TOMS O_3 during the September and October 1992 Global Tropospheric Experiment/Transport and Atmospheric Chemistry near the Equator-Atlantic (GTE/TRACE-A) DC-8 aircraft mission. Much of the near-Africa tropospheric O_3 maximum that was the focus of TRACE-A lies over persistent marine stratocumulus. TRACE-A flights in the eastern Atlantic, therefore, represented an excellent opportunity to validate the TOMS measurements. An example of corrected TOMS total O_3 from TRACE-A is shown in the second figure, along with the corresponding reflectivity. High reflectivity denotes the most intense stratocumulus coverage. The higher O_3 column corresponds to layers of high O_3 in the troposphere (especially between 4 and 12 km) that are largely due to seasonal biomass burning in



The difference, SBUV non-THIR (standard) total O_3 SBUV THIR total O_3 , versus SBUV reflectivities for August to October, 1979 to 1984. Only data for points with cloud-top height lower than 700 mb are used. The curve defines the polynomial relationship used to correct TOMS O_3 data for the eastern Atlantic in the region of persistent marine stratocumulus off southern Africa.

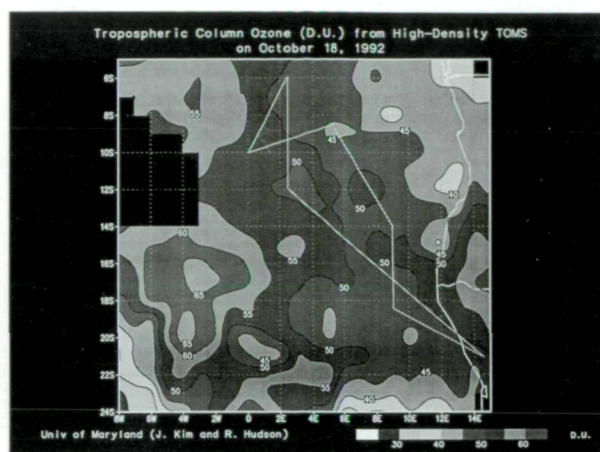
Africa and South America. These layers were observed directly by balloon-borne O_3 sensors launched from Ascension Island (8°S lat., 15°W long.).

From the second figure, one can see that even after correction, the highest O_3 values coincide with the location of marine stratocumulus. This is because the efficiency of TOMS retrieval falls off below 500 mb, except over a highly reflecting surface (e.g., snow or ice) or very low clouds, where it may exceed unity. This phenomenon has been exploited to derive the tropospheric O_3 column density (i.e., a measure of pollution) from high-density TOMS data. The third figure shows the tropospheric O_3 column depth for the same region and day as the second figure. Both real-time products (total O_3 from GSFC data and tropospheric O_3 from the University of Maryland data) were transmitted to the TRACE-A Science Team in Namibia for flight planning. TRACE-A Flight #15 took place on October 18, 1992, along the flight track shown in the third figure. The DC-8 had two Langley Research Center O_3 sensors on board. Integration of O_3 profiles taken from the DC-8 confirmed elevated O_3 levels at values in good agreement with the TOMS O_3 method.



(a) Total ozone in TRACE-A study region from Nimbus 7/TOMS gridded data for October 18, 1992; correction based on reflectivity (b) has been applied. Track for TRACE-A Flight #15 is shown.

Research in tropospheric O_3 from TOMS is continuing. The second figure also shows O_3 over the southern African continent suppressed relative to the eastern Atlantic by 5 to 10 DU despite the presence of biomass burning and some industrial pollution. The difference results from a combination of less efficient TOMS sensing of the lower troposphere and generally inadequate O_3 climatology in Africa and the tropics (i.e., very few ozonesonde observations). A large body of *in situ* O_3 observations collected on TRACE-A and the simultaneous Southern African Fire Atmospheric Regional Initiative (SAFARI) experiment will enrich existing climatology. GSFC researchers are working with other TRACE-A and SAFARI scientists to assemble an improved O_3 climatology from ground- and balloon-based O_3 measurements in the Congo; Ascen-



Tropospheric O_3 over marine stratocumulus region from high-density TOMS data. Flight track for TRACE-A Flight 15 is shown with the northernmost point and the small circles at 13°S marking location of DC-8 aircraft spirals. Integrating aircraft observations taken during the flight give tropospheric O_3 estimates in very good agreement with this satellite product.

sion Island; Pretoria; South Africa; Namibia; and aircraft data taken over eight southern African nations.

This work was done in collaboration with Dr. Robert Hudson, Chairman of the University of Maryland Department of Meteorology, and Jae-Hwan Kim, a graduate student at the University of Maryland studying under Prof. Hudson's direction.

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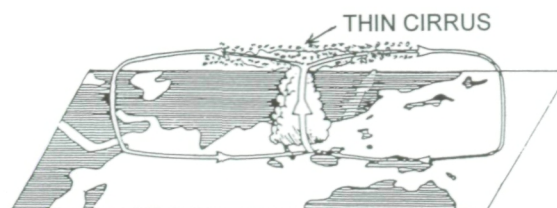
Dr. Anne Thompson, a member of the TRACE-A and TOMS science teams, has been at GSFC since 1984. Her research interests are in modeling tropospheric ozone in past and future atmospheres, using dynamical and photochemical models to analyze aircraft, ship-based and satellite data, and air-sea gas exchange.

Dr. Richard McPeters has been at GSFC working with backscattered ultraviolet instrumentation to measure ozone since 1976. He is currently the Nimbus-7 Project Scientist and Head of the Ozone Processing Team.

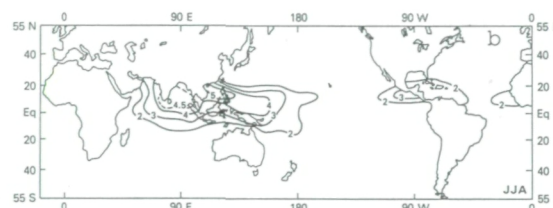
OPTICALLY THIN CIRRUS CLOUDS: RADIATIVE IMPACT ON THE WARMPOOL

OVER AN EXTENSIVE area of the equatorial western Pacific, SSTs exceeding 28 °C are present in all seasons. As an example, a climatological map of the SST for June, July, and August is shown in the first figure. This body of warm water—the largest in the ocean—is referred to as the warmpool, and constitutes a reservoir of heat energy that generates intensive convection over that region. Rising motions associated with convection are coupled to sinking motions over the cool waters of the eastern equatorial Pacific and the western equatorial Indian ocean (see the second figure). These rising and sinking motions are linked by horizontal flow of air in the upper troposphere at ~12 km, and near the sea surface, making up closed loops of circulation in the atmosphere near the Equator. This is known as the Walker circulation. The northeast and southwest monsoons in the atmosphere, which are responsible for the weather over a vast region of the globe, are strongly dependent on the presence of the warmpool and the Walker circulation. When the warmpool breaks down, the Walker circulation and the monsoons are also disrupted. Once every few years, such a breakdown, popularly referred to as an El Niño event, occurs, which is accompanied by anomalous weather. This interannual change of climate can have adverse economic effects.

An important question raised in this context is, how is the heat energy of the warmpool maintained? New evidence deduced from Nimbus-4 observations with an Infrared Interferometer Spectrometer (IRIS) and the observations made by ERBE satellites suggest that the optically thin cirrus clouds that are present in the cold upper troposphere play a key role in maintaining the warmpool. These thin cirrus clouds are made up of ice particles that spread from dense convective anvil clouds over an extensive area of the warmpool, as shown in the third figure. Solar radiation passes down through these clouds with relative ease while the upwelling infrared radiation is substantially trapped by them. As a consequence, these clouds produce a localized greenhouse effect and thereby maintain the warm temperature of the ocean underneath. These conclusions are consistent with theoretical models of radiation energy balance.



Schematic diagram showing Walker circulation over equatorial Pacific and Indian Oceans. Anvil clouds spreading at the top into thin cirrus are depicted.



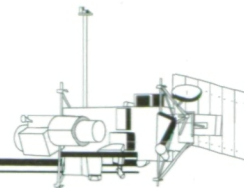
Percentage cloud cover due to optically thin cirrus in the tropics between 25°N and 25°S during June, July and August derived from Nimbus-4 IRIS observations. Contour value x10 gives percent cloud cover.

As demonstrated by these results, satellite observations, together with theoretical analysis, have the potential to explain the energetics and the onset of El Niño events, and provide additional justification for pursuit of other space-based Earth observations.

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Dr. Cuddapah Prabhakara is a Senior Research Scientist. He earned a PhD in Meteorology from the New York University. He has been at GSFC for 26 years, where he works in the Climate and Radiation Branch developing techniques to analyze satellite data.



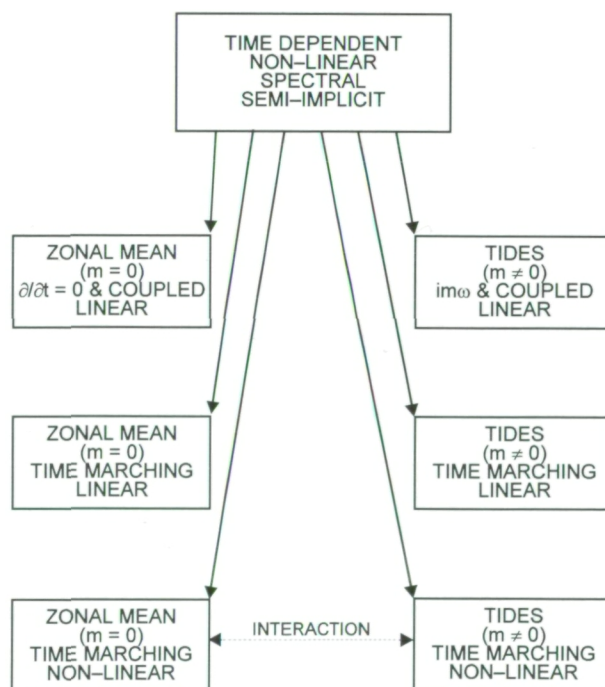
MODELING THE MIDDLE AND UPPER ATMOSPHERE

THE REGION of the Earth's middle (stratosphere and mesosphere) and upper atmosphere (thermosphere), extending from about 20 to 200 km is of considerable scientific and practical interest. This region is strongly influenced by the variable external sources associated with solar activities and anthropogenically induced chemical changes. Since its mass is only 5 percent that of the total atmosphere, the perturbations induced there are larger than those in the region near the ground and the changes are more readily detectable. This region constitutes a complex dynamical system. The observations and their coverage of the space and time domains being limited, this amounts to a complicated puzzle in which many of the important pieces are missing. An essential objective of modeling and theoretical development is to fill in these pieces, and to develop a coherent picture in which the phenomenology can be explained. In studying the dynamics of the middle and upper atmosphere, we need to perform global-scale simulation for an extensive region of the atmosphere. Existing models of the upper atmosphere generally do not go below 90 km. On the other hand, models of the middle atmosphere do not go above 120 km. The middle and upper atmospheric regions, therefore, cannot be coupled in these models. Yet ample evidence in ground-based and satellite observations indicate that it is essential to treat them as an integral system.

Distinct from the upper atmosphere, which is characterized by strong dissipation, the middle atmosphere represents a much more formidable fluid dynamical problem in that it is not weakly, but strongly nonlinear. We have developed a time-dependent, three-dimensional, fully nonlinear transformed spectral model to attack the problem. The spectral approach has the well-known advantage of being more efficient in low and moderate resolutions, and, unlike the finite-difference method, does not encounter singularity in the polar regions. Our formulation does not invoke hydrostatic nor inelastic approximations, and all linear waves (e.g., Rossby waves, gravity waves, acoustic waves) are exactly retained. The computation is performed efficiently because an implicit method is used to avoid severe time-step restrictions imposed by fast-traveling waves. To assure certain important conservation properties, the assumption is made that the horizontal density variations can be neglected in the nonlinear convection terms (but retained in the linear terms), and fluctuations higher than second order are ignored in the

energy equation. This limits the nonlinearity to quadratic order so that alias-free transformations can be performed, and the prognostic equations can be put in simple closed forms similar to those derived for standard spectral global circulation models (GCMs). De-aliasing then keeps the total mass and total angular momentum conserved, both formally and numerically. This model has the capability to account for the essential processes involved, and is able to synthesize the important interacting phenomena.

The spectral approach naturally decomposes the variable fields into separate zonal components whose individual behavior and interactions can be studied step by step. We exploit this convenience to develop a family of submodels that are very efficient in describing specific atmospheric phenomena. Since these models have a common root, they can also be readily assembled into a GCM, allowing us to develop successively more complete pictures. This methodology is illustrated in the first figure, where we show at the top the master model, from which derivatives are de-



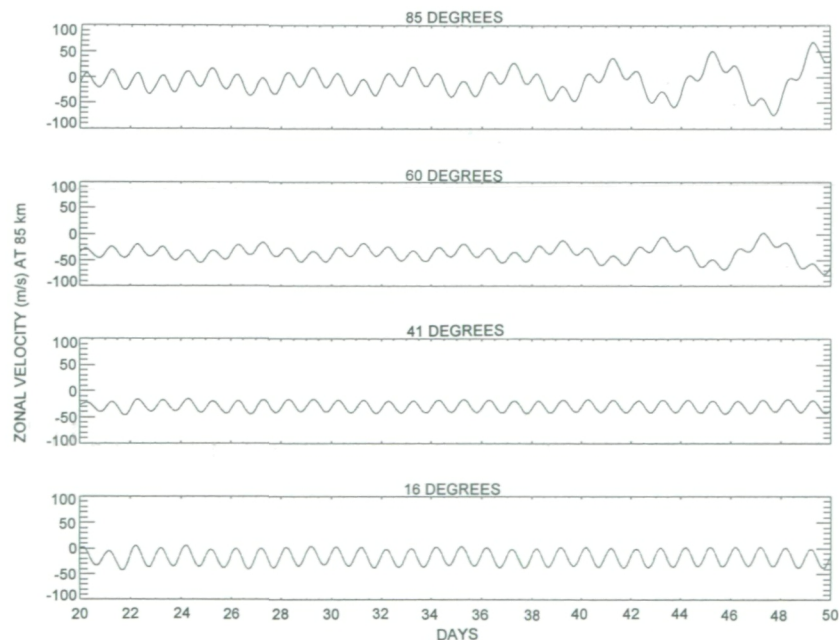
Block diagram illustrating the model for the middle and upper atmosphere, and the derivatives used in the analyses.

veloped that describe the mean zonal circulation (on the left) and the diurnal tides (on the right). In the submodels, we use both the time-marching and the steady-state formulations, which employ very different solution techniques. The steady-state solution formulation uses less computer time, but the time-marching formulation is more flexible in application. Although the two procedures are different, they produce identical results for the same test cases. This provides a test for the convergence of the time-marching procedure and demonstrates the reliability of the coding.

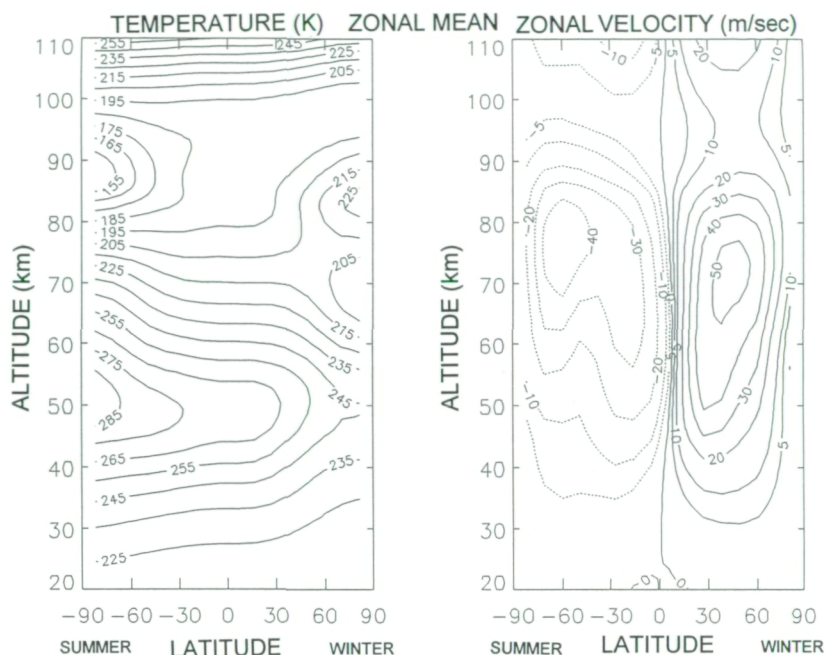
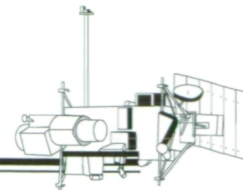
Our middle and upper atmosphere model has an altitude range going from the surface to 600 km. The global mean temperature and density distributions are taken as functions of height and are treated as fixed background. First, we apply our submodels to study the zonally averaged circulation. Similar to some earlier work of others, we use parameterizations for radiative cooling, eddy diffusion, and Rayleigh friction. The nonlinear solutions for the temperature variation and the zonal wind field under solstice conditions are shown in the second figure. They are in reasonable agreement with observations and the results of similar previous works. In particular, the anomalous temperature variations near the mesopause (~90 km)

are reproduced. The lowest temperature occurs in the summer pole instead of the winter pole, as would otherwise be expected from radiative considerations. This phenomenon is attributed to the redistribution of energy by a meridional circulation generated by gravity wave/mean-flow interactions, presently parameterized by Rayleigh friction. When this solution is compared to one in which nonlinearities are neglected (not shown) one finds that in general, the differences are small. In the nonlinear case, the temperature contrast between the summer and winter mesopause is slightly reduced, suggesting that the nonlinearity has a small dampening effect.

We applied our submodels to study the thermal atmospheric tides. These tides are generated in the water-vapor layer near the surface and in the ozone layer near 50 km, and are known to propagate to higher altitudes with growing amplitudes. Zonally averaged winds and temperature variations of the kind shown in the second figure can affect their development. The third figure shows the time-marching-based computed time series for the diurnally varying zonal velocities at 85-km altitude and at different latitudes in the summer hemisphere. Starting with zero amplitude at day zero, the diurnal amplitude is already well developed at day 20. But at higher latitudes,



Computed zonal mean temperature and wind fields for winter solstice.



Computed temporal variations in the zonal wind velocity at 85-km altitude and at different latitudes in the summer hemisphere.

the winds show a superimposed 4-day oscillation which grows in magnitude as time progresses. Analyses show that this oscillation, which has the form of a planetary wave, represents a baroclinic-type instability generated by the large horizontal temperature gradient associated with the mesospheric temperature anomaly. The effect of the background zonal velocities is small and tends to dampen the instability. The growth of this instability can be controlled by a locally enhanced diffusivity of $3 \times 10^6 \text{ cm}^2/\text{s}$, which would occur as stronger turbulence is generated.

More recent analyses show that the instability pattern becomes increasingly more complicated when higher order tidal modes are also considered. When the semidiurnal tide is included and non-linear interactions are allowed for, a 5-day wave replaces the 4-day wave.

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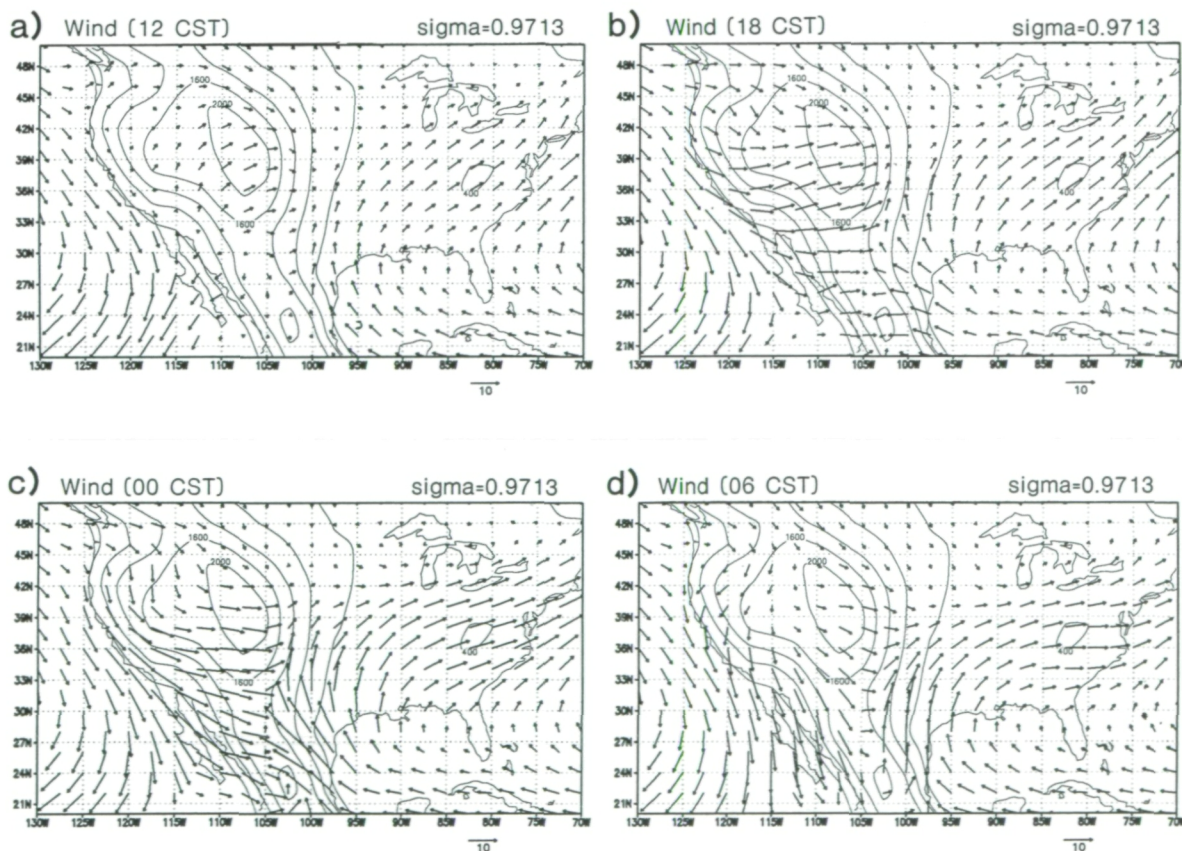
Dr. Kwing Chan, a Senior Scientist with Applied Research Corporation, is involved in solar and atmospheric research. Dr. Chan received his PhD from Princeton University and has been at GSFC for 13 years.

SIMULATION OF THE GREAT PLAINS LOW-LEVEL JET AND THE ASSOCIATED MOISTURE TRANSPORT OVER THE U.S.

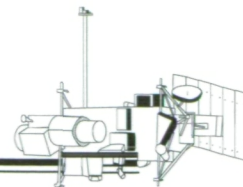
THE DYNAMICS of the atmosphere over the Great Plains region of the U.S. is characterized by the frequent formation of a low-level jet (LLJ). While the LLJ is generally confined to the lowest kilometer of the atmosphere, it may cover a substantial region of the Great Plains, and typically reaches maximum amplitudes of more than 20 m/s. The LLJ is found to occur at all times of the day, but the strongest and best-defined jets occur predominantly during the nighttime. The seasonal dependence is such that the LLJ tends to occur most often during the spring and late summer. Several mechanisms have been proposed to account for the generally strong low-level winds and/or the strong diurnal signal in the winds in this region. These include (1) the northward turning of the trade winds as they encounter the Rocky Mountains, (2) an inertial oscillation in the winds that occurs after the

daytime turbulence in the planetary boundary layer shuts off, and (3) the diurnal cycle in heating on sloped terrain east of the Rocky Mountains.

The location of the jet in the lowest kilometer of the atmosphere suggests that it is an important component of the atmospheric moisture budget in this region. However, the small vertical extent and diurnal nature of the jet has made it difficult from observations alone to study its detailed nature and its role in the continental-scale moisture budget. Data assimilation, by combining observations and short-term GCM forecasts, offers one of the best means of determining the atmosphere's moisture and wind fields at the resolution and accuracy necessary for computing moisture budgets. We recently performed a preliminary investigation of the LLJ as it is simulated by the GEOS-1



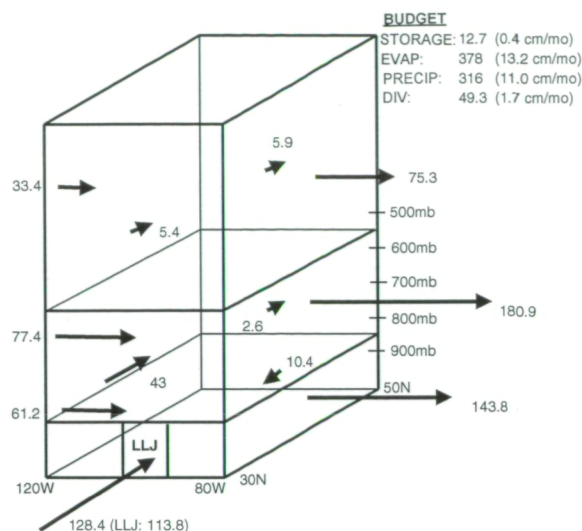
Wind vectors at the second σ level ($\sigma=0.9713$) for the 2-month (May/June) model simulation at the 4 synoptic times (units: m/s). The contours denote the surface height, and the contour interval is 400 m.



GCM. The GEOS-1 GCM is a key component of the data assimilation system being developed in the Goddard Laboratory for Atmospheres.

The GEOS-1 GCM was integrated for 2 months at a resolution of 2° latitude by 2.5° longitude at 20 σ -pressure levels using climatological boundary conditions. The integration was initiated from a GEOS analysis for 03 GMT, May 3 and ended at 03 GMT, July 2. The first figure shows the simulated low-level wind field at each synoptic time, averaged over the 2 months. The contours show the surface elevation. The development of the Great Plains LLJ during the course of the day appears to be a manifestation of the increasing penetration, between 18 and 00 CST, of an anticyclonic, subtropical Atlantic gyre (associated with the Bermuda High) into the North American continent from the Gulf of Mexico after surface friction over the continent has attenuated. The flow becomes increasingly convergent over the Mexican high plateau and northward along 105°W during this period; the flow also rotates anticyclonically consistent with the inertial oscillation. The Great Plains LLJ appears as the western branch of the anticyclonic gyre, which flows northward along the eastern slopes of the Rocky Mountains until about 35°N and then turns eastward to become part of the generally enhanced, westerly flow prevalent across much of the eastern U.S. at 00 CST.

The second figure shows the moisture fluxes and budget for the rectangular region approximately outlining the continental U.S. The fluxes are vertically integrated over three layers to highlight the differences in the low, middle, and upper levels of the atmosphere. The inflow from the southern boundary is dominated by the LLJ between about 102.5°W and 92.5°W . The other main source of moisture comes through the western boundary, primarily in the layer between 850 and 550 mb. The region occupied by the LLJ accounts for 32 percent of the net moisture entering through the southern and western boundaries. Very little moisture enters or leaves through the northern boundary. The primary outflow occurs through the eastern boundary below 550 mb. The moisture budget is characterized by a net divergence of moisture of $49.3 \times 10^6 \text{ kg/s}$, balanced by a net moisture source from evaporation which exceeds precipitation by $62 \times 10^6 \text{ kg/s}$, and a net storage of moisture of $12.7 \times 10^6 \text{ kg/s}$. The results of this investigation show that the GEOS-1 GCM does a credible job of reproducing the strong diurnal cycle in the low-level winds and moisture transports over the continental U.S. In particular, the GCM reproduces the pronounced Great Plains LLJ found in the observations. The springtime moisture



Time mean moisture flux and budget for the 2-month (May/June) model simulation for the continental U.S. (80°W to 120°W , 30°N to 50°N). The size of the region is $7.54 \times 10^6 \text{ km}^2$.

budget for the continental U.S. highlights the important role of the jet, which carries about one-third of the moisture entering the continent; slightly less than two-thirds of that amount enters during the 12 nighttime hours. Longer multi-year simulations are currently being performed to allow a better analysis of the variability of the LLJ and its interaction with the large-scale flow.

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Dr. Siegfried Schubert is a meteorologist in the Data Assimilation Office. Dr. Schubert has been at GSFC for 10 years after earning a PhD in Meteorology from the University of Wisconsin-Madison. Dr. Schubert's scientific interests are in low-frequency atmospheric variability, predictability, and the hydrological cycle.

MODELING TURBULENT DISPERSION OF POLLUTANTS

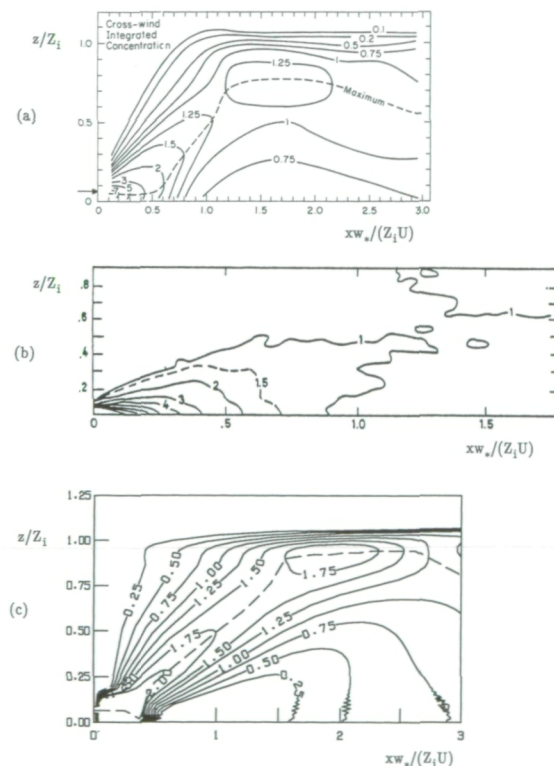
THE DISPERSION of pollutants in a turbulent medium is an unresolved problem of great scientific interest and practical importance. When the dispersion occurs over inhomogeneous terrain, as in most realistic cases, new complications arise. In spite of the work done in this field, many outstanding questions remain unanswered. For example:

- How do buoyancy and shear affect the concentration of pollutants (and the maximum ground-level concentration in particular) under unstable, neutral, and stable stratifications, even in flat terrain?
- What is the influence of gravity waves on dispersion?

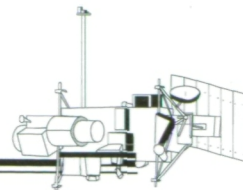
In an effort to address these questions, we have recently developed turbulence models which are described below.

a. *Second-order dispersion model over flat terrain in convective planetary boundary layer (PBL):* We studied the dispersion of a passive scalar from a continuous point source in the fully developed convective PBL. Clearly, a correct determination of the mean wind, mean temperature, and various turbulence quantities characterizing the PBL is crucial to a proper prediction of the space-time spread of the plume. These quantities were computed using a hydrostatic wind model with simplified second-order closures. A second-order closure dispersion model was formulated in three-dimensions and implemented assuming horizontal homogeneity as follows: we assumed a Gaussian distribution for the cross-wind spread of plume and the three-dimensional problem was reduced to a two-dimensional one by integrating the dispersion model equations over the cross-wind direction. The resulting dispersion model equations in two dimensions were solved for the laterally integrated concentration. A Gaussian distribution was used as the initial concentration field. Although the final equilibrium concentration distribution is not Gaussian, the initial values, so long as they are not too far removed from the equilibrium values, will only affect the rapidity with which an equilibrium distribution is achieved. Near the plume source, the Gaussian distribution also serves as a boundary condition to represent the source. The most crucial part of the dispersion model is the parameterizations of the following quantities: diffusion of the concentration flux by the turbulent velocity fluctuations; diffusion of the concentration temperature correlation; molecular destruction of the concentration

temperature correlation; and pressure concentration correlation. For all of the diffusion terms, we adopted the standard down-gradient approximation; for the destruction term, we introduced a new length scale which was assumed to be proportional to the length scale characterizing the mechanical dissipation; and for the pressure term, we included a buoyancy contribution suggested by Large Eddy Simulations (LES). As compared with experiments and Lagrangian calculations, the second-order closure model gives satisfactory but not excellent results (the first figure).

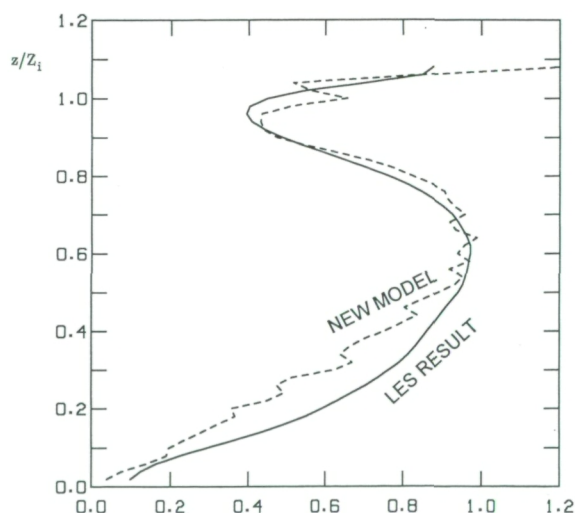


Plot of the concentration C (integrated across wind) as a function of height. The horizontal axis represents the distance from the source x , scaled in appropriate units. The dashed line represents the plume's maximum centerline. Panel (a): tank experiment; panel (b): Lagrangian model; panel (c): second-order dispersion model. The turbulent wind and temperature fields were from a second-order flow model.



b. Improving turbulence modeling: The turbulence closure models can be improved using LES data and recent theoretical advances. We employed the following new or modified closure schemes:

- (1) The dissipation rate ϵ of the turbulent kinetic energy (or the length scale ℓ_ϵ associated with it) is one of the most important and least understood parts of turbulence modeling. Starting from a theoretical formulation of the buoyancy spectrum in stably stratified flow, we have derived an expression for ℓ_ϵ that includes both buoyancy and shear; encompasses all the models of ℓ_ϵ proposed by others; behaves well for small buoyancy and/or shear; and explains the non-monotonic behavior of ℓ_ϵ found in LES calculations (the second figure). We have also proposed a model for ℓ_ϵ which may be useful when the heat flux is prescribed or solved predictively.
- (2) We developed an Improved Algebraic Reynolds Stress Model with buoyancy that captures more of the advection and diffusion contributions so that it can be expected to work better, especially in the complex terrain cases where nonlocal phenomena are often dominant. This approach also leads to explicit solutions that yield Reynolds stresses and heat fluxes



ℓ_ϵ normalized by the mixed layer depth Z as a function of the normalized height z/Z_i according to the new model of ℓ_ϵ (dashed line) and according to recent LES data for a shear-dominated ABL with an inversion cap. The S-shaped ℓ_ϵ predicted by the LES calculations is reproduced by the new model.

directly in terms of the gradients of the mean velocity and temperature fields without having to neglect (due to difficulties in inverting a large matrix) some of the important terms in the pressure correlations, so more physics can be captured.

- (3) Third-order moments in the turbulent flow field are important not only because they affect the value of the second-order moments, but also because they directly affect the concentration field (e.g., control the plume ascent and descent). The usual down-gradient approximation for the third-order moments often fails as evidenced by LES data. We obtained a much more complete description of the third-order moments by considering their dynamical equations, which in the stationary case reduce to a set of algebraic equations. The resulting third-order moments reveal a universal structure considerably more general than the down-gradient approximation, and can serve as a guide in the parameterization of the third-order moments appearing in the concentration equations.
- (4) The time scales in the pressure velocity and pressure scalar correlations have been inappropriately taken as proportional to the mechanical dissipation time scale. For the convective PBL, we recently derived a new expression for the time scale of the dissipation of temperature variance, which is a smaller time scale in stably stratified flow and so represents more realistically the pressure correlation processes.

With the above new closure parameterizations, both the second-order closure dispersion model and the non-hydrostatic wind model, which we intend to use to provide inputs to the dispersion model, can be significantly improved. The new dispersion model is especially appropriate for the case of complex terrain.

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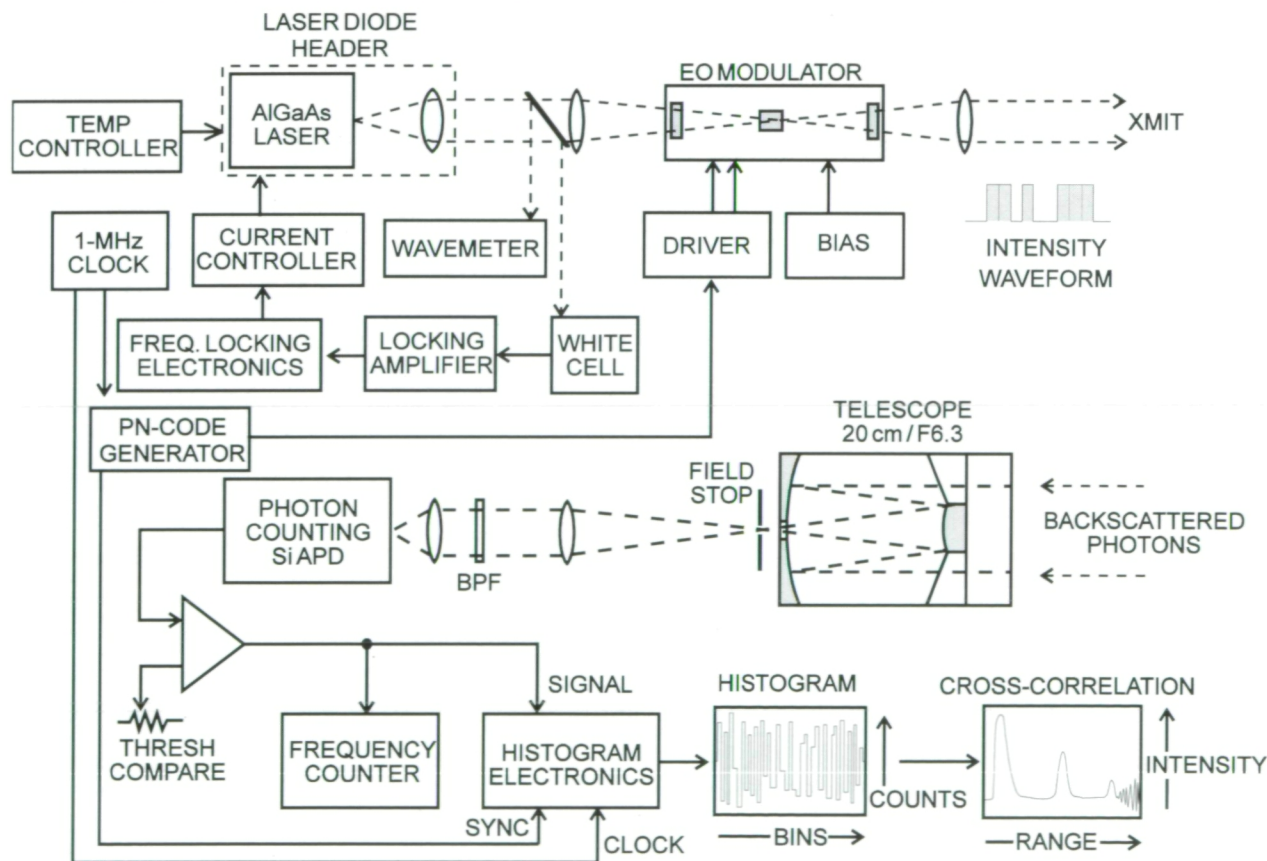
Dr. Y. Cheng holds a PhD in Physics. His professional interests include theoretical modeling and numerical simulation of turbulence phenomena.

DIFFERENTIAL ABSORPTION LIDAR MEASUREMENTS OF TROPOSPHERIC WATER VAPOR USING ALUMINUM-GALLIUM-ARSENIDE LASERS MODULATED WITH PSEUDORANDOM CODES

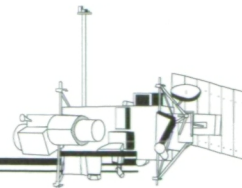
ALUMINUM-GALLIUM-ARSENIDE (AlGaAs) lasers provide a small, lightweight, and efficient optical source for lidar transmitters. When compared to monopulse lidar transmitters, they are limited in peak power, but are capable of high average transmitted power. Atmospheric lidar profiles have been measured using a quasi-continuous wave (CW)-transmitted signal by means of pseudorandom-noise (PN) amplitude modulation. A PN code-modulated laser beam is transmitted through the atmosphere, with only a small fraction—less than one photon per bit—of the transmitted signal backscattered to the receiver. The receiver detects these photons and accumulates a photoelectron count over many repetitions of the code. This accumulated count is presented as a histogram of photoelectron counts versus time delay (expressed as counts per bin). On average, the histogram represents the convolution of the atmospheric backscatter function with the transmitted code. The correlation properties of the PN

code permit recovery of the atmospheric response by correlation of the histogram with the transmitted bit sequence.

We have developed and tested a prototype water-vapor differential absorption lidar (DIAL) based on a previously developed PN code AlGaAs lidar system. A system diagram is shown in the first figure; system parameters are listed in the table. The system uses a single 100-mW AlGaAs laser operating in CW mode, externally modulated with a variable-length PN code at a bit rate of up to 2 MHz. The laser diode wavelength is locked to one of several water-vapor absorption lines near 812 nm using a 10-m path length white cell, a locking amplifier, and feedback electronics. A 20-mV dither current is applied to the laser and used to generate the error signal, which is used as feedback to the laser. To make DIAL measurements, backscatter data are taken both while the laser is locked to the center of an absorption line and while its wave-



Water-vapor differential absorption lidar system diagram.

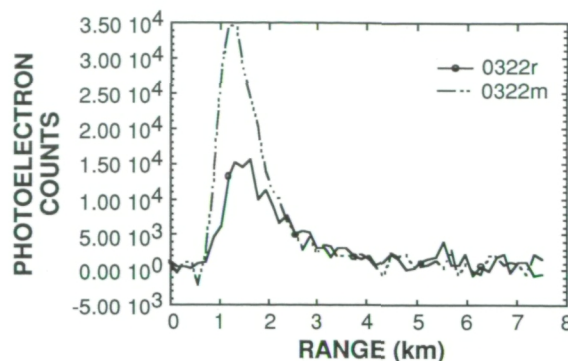


Prototype AlGaAs Lidar Characteristics

Laser Type	AlGaAs Laser Diode, Spectra Diode Labs 5410-G1
Laser Modulator	Conoptics KD*P Electro Optic Modulator
Collimating Lens	Corning Single Element Asphere
PN Code	4095 bit, 1-MHz bit time
Range Resolution	1 μ sec, 150 meters
Telescope	20 cm diameter, f6.3
Interference Filter	810 nm, 10-nm bandpass
Detector	Photon-Counting Si APD
Discriminator	Tennelec TC 453 Constant Fraction

length is tuned slightly off the absorption line; this normalizes the elastic scattering common to both signals. The logarithm of the ratio of the two signals is proportional to the number density of water molecules.

The second figure shows nighttime water-vapor DIAL measurements over a nearly horizontal path (2 to 3° elevation angle) through the PBL. A 4095-bit code was transmitted at 1 MHz, providing range resolution of 150 m/bit. The average transmit power was ~35 mW; integration time was 300 seconds. Dataset 0322m shows the lidar return with the laser tuned to 12,353 cm^{-1} , a window region, while dataset 0322r shows the lidar return with the laser tuned to 12,365 cm^{-1} , a region of relatively strong absorption. It should be noted that the laser was not actively frequency-stabilized for these measurements. However, the laser was observed to be stable to better than 1 cm^{-1} during the integration period. The difference in the two lidar signals is due primarily to two effects, the difference in water-vapor absorption cross section at the two wavelengths, and the difference in modulation index due to the sensitivity of the electro-optic (EO) modulator to changes in laser wavelength. While the data shown in the



Range-resolved horizontal path water-vapor DIAL measurements.

second figure do not permit a quantitative estimation of water molecule number density, they do suggest that with further effort, water-vapor DIAL measurements with PN code-modulated AlGaAs lasers are possible.

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BIOSPHERE

EVALUATING THE EFFECTS OF UV-B AND UV-A IRRADIANCES ON PLANT PIGMENTS, PHOTOSYNTHESIS AND GROWTH IN *GLYCINE MAX* L

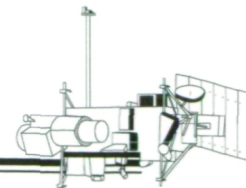
ONE OF THE MOST serious—and possibly most controversial—environmental issues of this decade is the chemical depletion of the Earth's protective stratospheric ozone layer, and the consequences for living organisms. In the past decade, substantial ozone depletion was documented by NASA in the polar regions of the Earth; recently, concern has been raised that ozone depletion may affect mid-latitude regions as well. It is generally acknowledged that a thinner ozone layer enables increased atmospheric transmittance to the Earth's surface of the ultraviolet (UV) component of the solar radiation ($\lambda < 0.400 \mu\text{m}$), especially the biologically dangerous UV-B irradiance ($0.290\text{--}0.320 \mu\text{m}$). However, many issues are still not adequately known, including the long-term rate of ozone degradation and possibility of recovery; the rate of reduction of manmade ozone-depleting chemicals; the role of natural chemical sources; the spatial and annual variations in ozone and transmitted UV; the effect of increased UV exposure on humans, crops, terrestrial and marine ecosystems; and the types of protective responses, as well as their underlying physiological mechanisms, invoked by UV exposure in plants.

Since plants are critical for food supply, and because disruptions in the terrestrial and marine ecosystems could affect global carbon, water, and energy balance, determining how plants are affected by enhanced UV-B irradiation has been the focus of research undertaken over the last 2 decades by a small number of government and university centers in the U.S. and Europe. Numerous studies have demonstrated that UV-B radiation is harmful to plants, with the most common impairment being reduced photosynthetic function. However, many studies reporting detrimental effects of UV-B radiation on plants were conducted under relatively low visible-light levels (photosynthetic photon flux (PPF) < 500 to $800 \mu\text{mol}/\text{m}^2/\text{s}$). In contrast, studies conducted under high PPF ($> 1,000 \mu\text{mol}/\text{m}^2/\text{s}$) show fewer detrimental effects, due in part to photorepair of DNA damage, an enzyme-activated process initiated by blue (0.400 to $0.500 \mu\text{m}$) and UV-A (0.320 to $0.400 \mu\text{m}$) radiation. (Note: for midday in the summertime in mid-latitude regions, PPF $\sim 2,000 \mu\text{mol}/\text{m}^2/\text{s}$.) UV-B radiation also stimulates increased leaf production of UV-B absorbing compounds (e.g., flavonoids), which act as screening pigments and are thought to protect photosynthetic tissue from UV-B damage. In general,

the mechanisms underlying plant response to UV-B irradiation are not well understood, including the manner in which UV-B interacts with longer wavelength UV-A and visible radiation to alter photosynthetic performance.

The ability to determine plant response to enhanced UV-B irradiation is influenced by the experimental procedures employed. In the traditional experimental protocol for UV-B studies, artificial irradiation is supplied by a fluorescent lamp and filter combination that provides both biologically effective UV-B (UV-B_{BE}) and UV-A radiation. The UV-B effect is determined as the difference between observed plant responses to a UV-B treatment (UV-B_{BE} + UV-A irradiation) and its control (UV-A irradiation only). Whereas great care is exercised in determining and controlling the UV-B_{BE} dosage, the concomitant UV-A dose was not monitored previously. The potential role of UV-A radiation on plant response in UV-B studies is important because a large number of biosynthetic processes are UV-A/blue-light stimulated or regulated, including the synthesis of chlorophylls and carotenoids, the primary photopigments. In natural environments, plants receiving high UV-B irradiance also receive high UV-A flux and PPF, and benefit from photorepair processes. Artificial UV-A irradiance influences on plant response are most important in glasshouses, where natural solar UV-A radiation is restricted by the glass acting as a cut-off filter at $\sim 0.350 \mu\text{m}$, or in growth chamber environments where solar UV-A and visible fluxes are lacking altogether. In addition, most of the preliminary studies are conducted in glasshouses, where many relevant environmental conditions can be controlled, before larger or longer term field studies are initiated.

The work described here investigated the potential interaction (or coaction) between UV-B and UV-A radiation, and its effect on the interpretation of plant response in glasshouse UV-B studies. The relationship of UV-B-absorbing compound levels to photosynthetic pigment content and photosynthetic performance was also examined, utilizing soybean (*Glycine max* L.)—an important crop with well-known genetic lines. Analogous pure genetic lines (i.e., isolines) for normal, chlorophyll-deficient, and flavonoid-deficient pigment levels of two soybean cultivars with different total pigment levels were included in several factorial experiments, conducted under high PPF

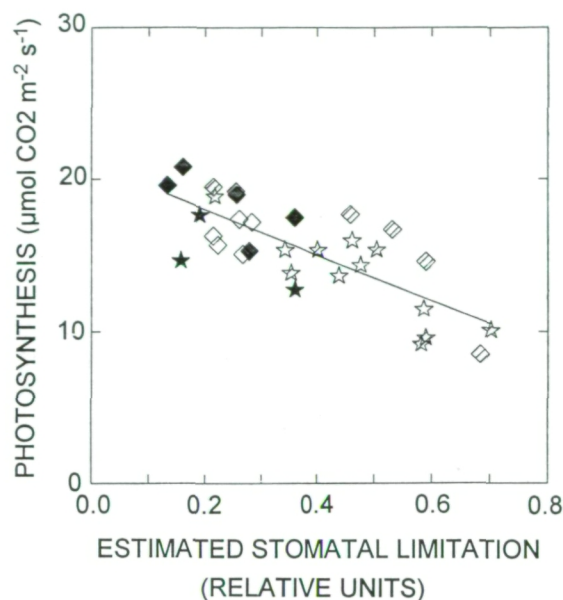


in a glasshouse where the UV-A irradiance associated with the UV-B treatments was controlled.

The first phase of the study focused on the artificial UV-A irradiation produced by UV-B treatments. Significant differences were found in UV-A irradiances among treatments and controls, and with filter photodegradation, unless specifically controlled. Also, the artificial UV-A and UV-B irradiances produced by lamps at different doses were correlated. For example, the filtered lamp irradiances for two different daily UV-B_{BE} doses of 10.7 and 14.1 kJ/m² were associated with concomitant daily UV-A doses of ~5 and ~9 kJ/m². Differences were maintained when the natural solar UV-A transmitted into the glasshouse (λ 0.350) was considered. These effects are most severe in winter glasshouse (and in growth chamber) studies, but also persisted in the maximum natural-light conditions of mid-summer in College Park, MD (39°N lat.).

When the artificial UV-A irradiances were matched between treatment and control pairs for the two doses described above, several responses were apparent. First, no relationship was found between UV-B-absorbing compound levels and any measure of photosynthesis capacity evaluated; however, these compounds were correlated with biomass and with total carotenoids in UV-B irradiated plants only. Second, photosynthetic pigments, especially carotenoids, accumulated in leaves when exposed to UV-B- irradiation in all experiments; chlorophyll *a/b* ratios were significantly lower, and were correlated with carotenoid content in UV-B irradiated plants only. This indicates that increasing linear electron transport in the photosystems, located in the chloroplasts, may be involved in photoprotection from UV-B damage. Since total chlorophyll content increased, but photosynthetic capacity was not greatly affected in UV-B irradiated plants, the calculated photosynthetic efficiency (net photosynthesis per unit chlorophyll) decreased. Photosynthetic efficiency also decreased as total carotenoid content increased in all plants, indicating a cost in the relative carbon gain associated with the higher accumulation of carotenoids in UV-B irradiated plants. Third, no direct photosystem damage was observed, as is commonly assumed, in UV-B-irradiated plants in this series of experiments conducted under high ambient PPF (1200 $\mu\text{mol}/\text{m}^2/\text{s}$). Rather, observed reductions in photosynthesis were attributed primarily to a UV-B-induced stomatal closure (see the figure).

Overall, many variables exhibited an interaction between spectral quality and quantity, interpreted as moderation of UV-B effects by UV-A irradiation. This is similar to



The estimated relative stomatal limitation to photosynthesis was calculated as $[(P_{O_2} - P_{CO_2})/P_{O_2}]$, where P_{O_2} is the maximum net photosynthetic capacity based on oxygen evolution, and P_{CO_2} is the net photosynthesis based on carbon dioxide exchange. This increase in stomatal influence for UV-B-irradiated plants from one glasshouse experiment is presented as a function of P_{CO_2} . An inverse linear relationship ($r^2 = 0.66$, $P < 0.001$) is shown for UV-B irradiated plants; no stomatal limitation was evident in control plants (not shown). Symbols: stars = high UV-B treatment; diamonds, low UV-B treatment. Filled symbols = normal isolines; hatched symbols = flavonoid-deficient isolines; open symbols = Chl-deficient isolines.

previously observed amelioration of UV-B effects by visible radiation. An explanation for the common failure to verify a dose-related response in UV-B studies was also provided: the plant responses to a low UV-B dose were often greater than those to a high UV-B dose; also, differences in responses between the low UV-B dose and its UV-A control were often more clearly separable. Furthermore, plant response at two-dose levels can be difficult to interpret since irradiances in both the UV-B and UV-A wavebands increase at higher biologically effective artificial UV-B doses. These results were further supported by response of pigments to three treatments with different UV-B_{BE}:UV-A ratios (<0.5, for total UV-A). In general, UV-B-initiated photoprotection was found to be more

complex than is usually assumed, and involves photosynthetic pigments in addition to flavonoids.

A change in the experimental protocol for glasshouse studies was recommended, whereby the UV-B_{BE} irradiance is varied against a standard, high-UV-A and ambient visible-light background. In this design, the traditional UV-A controls would be eliminated and replaced with a treatment producing a relatively low UV-B_{BE}:UV-A ratio (e.g., either the ambient value or the local value representative of pre-industrial 0-percent ozone depletion). This design confers several advantages: it allows the testing for dose dependency of responses; UV-B_{BE}:UV-A ratios per treatment are constant, whether computed on the basis of lamp or total UV-A irradiances; and this protocol is similar to that utilized in field studies, where all artificial treatments also receive natural solar UV-B (and longer wavelength) irradiation.

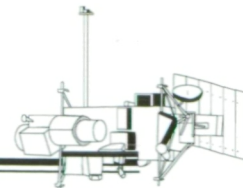
The UV research described was conducted at the University of Maryland in cooperation with Dr. Alan Teramura

of the Department of Botany as part of dissertation research sponsored by NASA through its part-time graduate studies program, and was partially funded by the USDA Competitive Grants Program.

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Sponsor: Office of Mission to Planet Earth

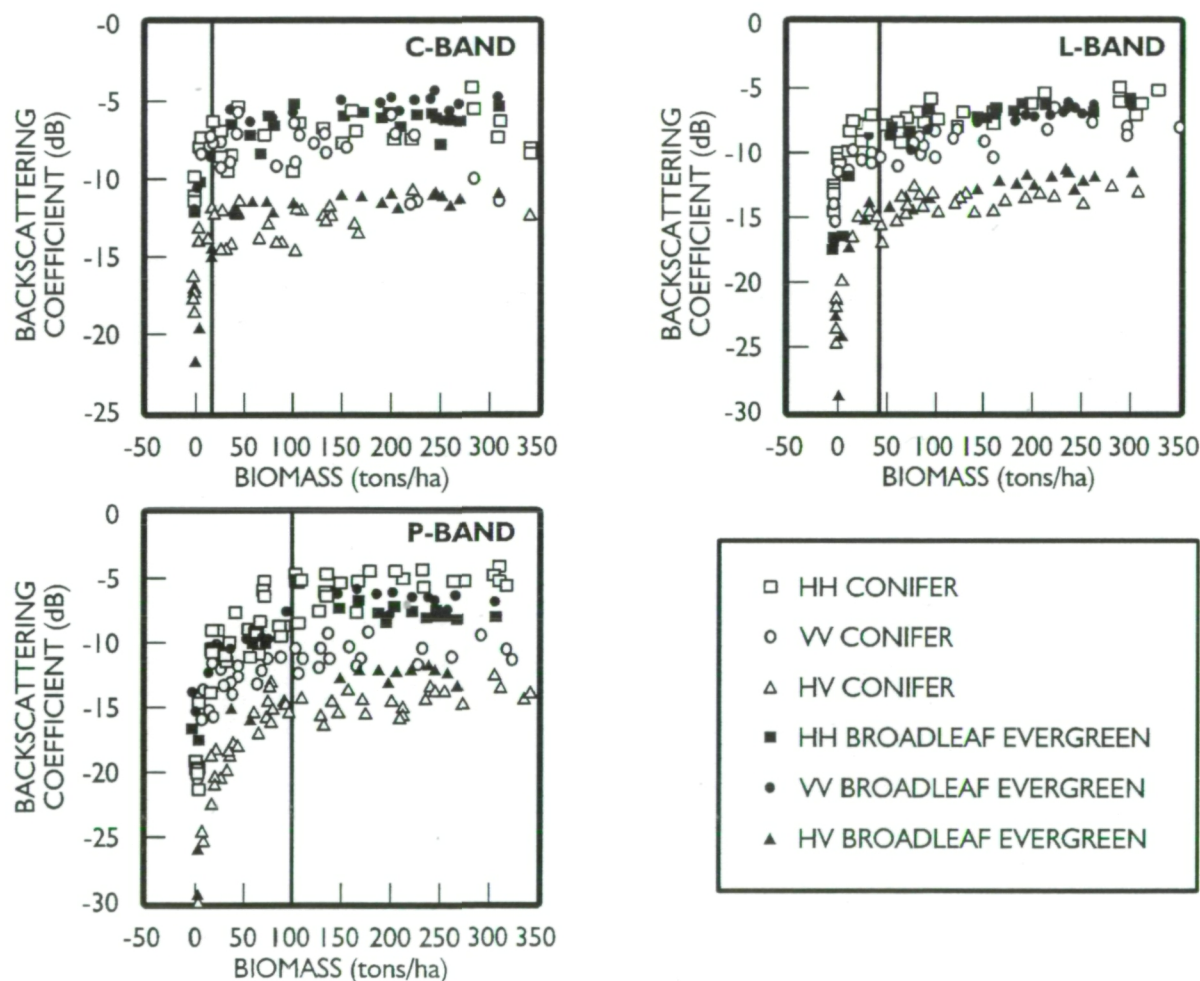
Dr. Elizabeth Middleton is a research scientist in the Laboratory for Terrestrial Physics. She is a Boreal-Ecosystem Atmosphere Study (BOREAS) Principal Investigator and Co-Investigator, an International Satellite Land Surface Climatology Project (ISLSCP) Co-Investigator, a FIFE (First ISLSCP) Co-Principal Investigator, and invited participant in many field campaigns. Dr. Middleton has been at GSFC for over 15 years, 10 of which have been with the Biospheric Sciences Branch (923).



RADAR SIGNAL SATURATION AND FOREST BIOMASS: ARE CURRENT SENSORS ADEQUATE FOR GLOBAL CARBON MODELING?

ONE OF THE PRIMARY measurement objectives for NASA's Mission to Planet Earth is to determine the quantity and location of the Earth's terrestrial vegetation or biomass. Since terrestrial vegetation acts as both a source and a sink of CO_2 , biomass measures are required to accurately model the cycling of carbon between the atmosphere and biosphere and for making predictions of climate change, such as global warming.

Recently, SAR was identified as a potential tool for making global biomass measures because radar penetrates cloud cover and interacts with the structure of the vegetation. While many studies have shown that correlations can be derived between radar backscatter and biomass, saturation points, or the biomass level where radar backscatter no longer increases have also been reported for P-, L-, and C-band radar systems. The Biospheric Sci-



Calibrated SAR backscatter plotted against total above-ground dry biomass, in metric tons per hectare (tons/ha) for broadleaf evergreen forests in Hawaii, and conifer stands (*Pinus* spp.) in North Carolina and France. Estimated saturation points are shown by the vertical lines intersecting the x-axis, where practical functionality ends with respect to predicting biomass from the radar signal.

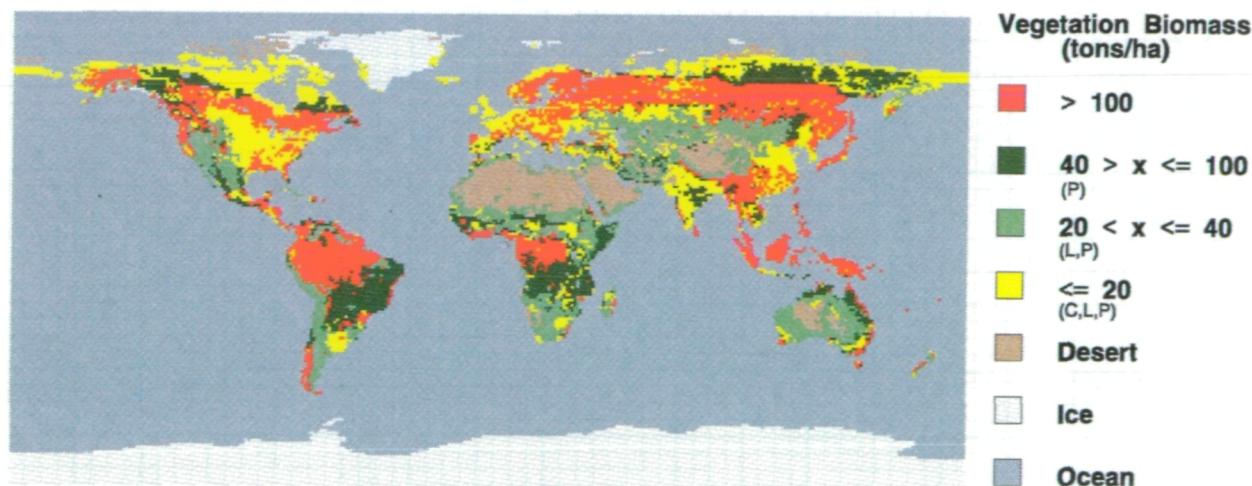
ences Branch at GSFC, in conjunction with Stanford University, carried out a project to address the question of SAR signal saturation with respect to forest biomass. The study focused on two questions: How universal, in terms of different forest types, is the phenomenon of SAR backscatter saturation with respect to biomass? How could it impact attempts to use SAR sensors to make global biomass inventories?

The assessment of the saturation phenomenon was made using results from studies carried out on two different forest types: tropical broadleaf evergreen forests in Hawaii, and a combined dataset of coniferous forest stands from North America and Europe. The forest stands observed in these studies differed considerably with respect to both individual morphology and stand structure, but had similar ranges of total above-ground dry biomass. The SAR data consisted of C-, L-, and P-band (5.3, 1.25, and 0.44 GHz) quadpolarized images collected by the NASA/DC-8-mounted JPL SAR at an incidence angle of approximately 45°. All data were calibrated using identical procedures. Backscatter statistics for both forested areas were compared to biomass data collected in the field and plotted together (the first figure). Despite their substantial structural differences, the two forest types had similar SAR response curves with respect to biomass saturation. The saturation levels identified were: ≈ 20 tons/ha for C-band, ≈ 40 tons/ha for L-band, and ≈ 100 tons/ha for P-band. The possible existence of a universal saturation point for the SAR response to forest biomass distinctly limits the

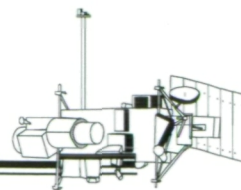
usefulness of P-, L-, and C-band SAR for global biomass mapping. Vegetated areas falling below the backscatter/biomass thresholds for a particular SAR frequency and polarization might be profitably mapped by SAR, but forested areas with biomass levels above the saturation point are out of the range of further categorization.

To assess the impact of saturation on the utility of P-, L-, and C-band SAR for global biomass mapping, the backscatter/biomass saturation limits were matched to a global-scale database of vegetation types with estimated biomass. Four SAR applicability classes were defined.

- Class 1: based on C-band threshold, represents vegetated systems having 20 tons/ha total biomass. All three SAR bands (C-, L-, and P-) could be used to map biomass within these areas.
- Class 2: based on L-band threshold for the upper limit, represents forests where only L- and P-bands are suitable (i.e., vegetated systems having between 20 and 40 tons/ha total biomass).
- Class 3: represents vegetation types where only P-band is useful (i.e. vegetated systems having between 40 and 100 tons/ha total biomass).
- Class 4: the exclusion class, represents vegetated systems that have biomass levels above 100 tons/ha (the saturation point for P-band).



Global vegetation map classified according to SAR biomass thresholds. Red represents forest ecosystems having biomass levels that are above the range of current SAR sensors.



Results from the database analyses showed that approximately 38 percent of the world's vegetated surface area containing nearly 81 percent of the estimated total store of terrestrial plant biomass lies in Class 4, which is above the saturation limit of the current radar systems. While 62 percent of Earth's vegetated surface area falls below the saturation level for P-band, these classes contain only an estimated 19 percent of the total biomass represented by terrestrial vegetation. Only 4 percent of Earth's terrestrial biomass is accessible using C-band (Class 1: vegetation stands of 20 tons/ha) where the ERS-1 C-band SAR might be useful. L-band, with its slightly higher threshold, picks up only another 3.5 percent of Earth's biomass (Class 2) for a total of 7.5 percent existing in vegetated systems with 40 tons/ha biomass. L-band systems such as JERS-1 SAR fall into this range. P-band, having the highest threshold, only accounts for another 11 to 12 percent of the Earth's estimated total biomass (the second figure).

The prospect that current SAR sensors will meet global biomass mapping objectives could be substantially limited given the results found here. New techniques and even new instruments, possibly using longer wavelength radar and smaller incidence angles, need to be developed to measure the bulk of the world's biomass.

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Sponsor: Office of Mission to Planet Earth

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SOLID EARTH

IMPACT CRATERING IN THE GEOLOGIC RECORD

THE AGES OF A NUMBER of Cenozoic impact craters are now known accurately enough that they can be placed fairly precisely in the geologic record. For example, a huge structure of probable impact origin, Chicxulub in Mexico, and the more moderately sized Manson Crater in the U.S., are closely associated in time with the Cretaceous/Tertiary boundary extinctions 65 million years ago. If it were found that smaller craters also correlate with geologic-stage boundaries, one might infer that impacts of several extraterrestrial bodies sometimes occur in brief, but powerful showers. It would then be unnecessary to identify an individual very large crater as the actual "smoking gun" in a boundary extinction event. Other kinds of physical evidence, like shocked quartz and an excess of rare siderophile elements (e.g., iridium) in strata of appropriate age, can also be looked for, but such evidence is currently available for only a very few Phanerozoic period boundaries and, in a convincing way, only for the Cretaceous/Tertiary boundary.

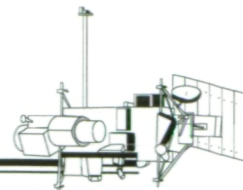
In order to investigate a possible correlation between the ages of impact craters and of geologic-stage boundaries, two different approaches can be used. The first approach is to spectrally analyze the two time series and to look for

similar patterns of periodicity. Unfortunately, a case recently made in this way for an approximate 30-million-year periodicity now appears to be very weak as more and better age data have become available. In any case, the method is indirect. The second approach, used by us in the analysis presented here, is the more direct one of cross-correlation of the two series. A longstanding problem of how to cross-correlate two point series has recently been solved by using a technique originally designed for linear spectral analysis of a single point series, in which the given series is, in effect, cross-correlated with a template series consisting of equally spaced points. Here the series of interest consists of the impact crater ages, and the template series is the formal geologic time scale (i.e., the stage boundary ages). Monte Carlo methods are used to incorporate into the analysis the Gaussian analytical errors of the ages, and to estimate the statistical significance level of the derived correlation.

Altogether, a set of 11 Cenozoic craters meets the combined requirements of small analytical age errors (not more than ± 1 million years), significant crater diameters (at least 2 km), and approximate stationarity of the resulting time series. Wherever possible, the accuracy of each crater's

Well-Dated Large Cenozoic Impact Craters and the Nearest Geologic Stage Boundaries

Impact Crater	Diameter (km)	Age (Myr)	Stage Boundary	Boundary Age (Myr)
Zhamanshin	13	00.9 $\pm$ 0.1	Piacenzian/Calabrian	1.63 $\pm$ 0.03
Bosumtwi	10	01.3 $\pm$ 0.2	Piacenzian/Calabrian	1.63 $\pm$ 0.03
New Quebec	03	01.4 $\pm$ 0.1	Piacenzian/Calabrian	1.63 $\pm$ 0.03
Elgygytgyn	18	03.5 $\pm$ 0.5	Zanclian/Piacenzian	3.40 $\pm$ 1.00
Roter Kamm	02	03.7 $\pm$ 0.3	Zanclian/Piacenzian	3.40 $\pm$ 1.00
Ries	24	14.8 $\pm$ 0.7	Langhian/Serravallian	14.8 $\pm$ 1.00
Steinheim	04	14.8 $\pm$ 0.7	Langhian/Serravallian	14.8 $\pm$ 1.00
Haughton	20	23.4 $\pm$ 1.0	Chattian/Aquitania	24.1 $\pm$ 1.00
Montagnais	45	50.5 $\pm$ 0.8	Ypresian/Lutetian	50.3 $\pm$ 1.00
Chicxulub	180	65.0 $\pm$ 0.1	Maastrichtian/Danian	66.0 $\pm$ 1.00
Manson	35	65.7 $\pm$ 1.0	Maastrichtian/Danian	66.0 $\pm$ 1.00



age has been checked by intercomparing $^{40}\text{K}/^{40}\text{Ar}$, $^{40}\text{Ar}/^{39}\text{Ar}$, fission track, and tektite-strewn field ages. In all cases, the various ages agree within ± 1 million years. In addition, the geologic time scale shows comparatively small analytical errors for Cenozoic time, during which the average length of the geologic stages was 3.8 million years.

Visual inspection of the collected data (shown in the table) reveals an apparently tight correlation between the accurately dated impact craters and the geologic-stage boundaries. Subdivision of the full set of 11 craters can be made by either crater size or crater age. Seven craters have diameters greater than 5 km; six are older than the mid-Miocene; and five are younger than the mid-Miocene. When the number of craters in the sample is thus increased from 5 to 6, then to 7, and then to 11, and the derived correlations are tested for statistical significance, the estimated significance levels decline from 4 percent to 2 percent, to 1.4 percent, to 0.2 percent. Just the opposite trend would be expected for a random distribution of crater ages. In other words, the correlation is highly significant.

The formal spread of the residuals derived from the correlation analysis is approximately 2 million years, which agrees with the typical length of an observed extinction

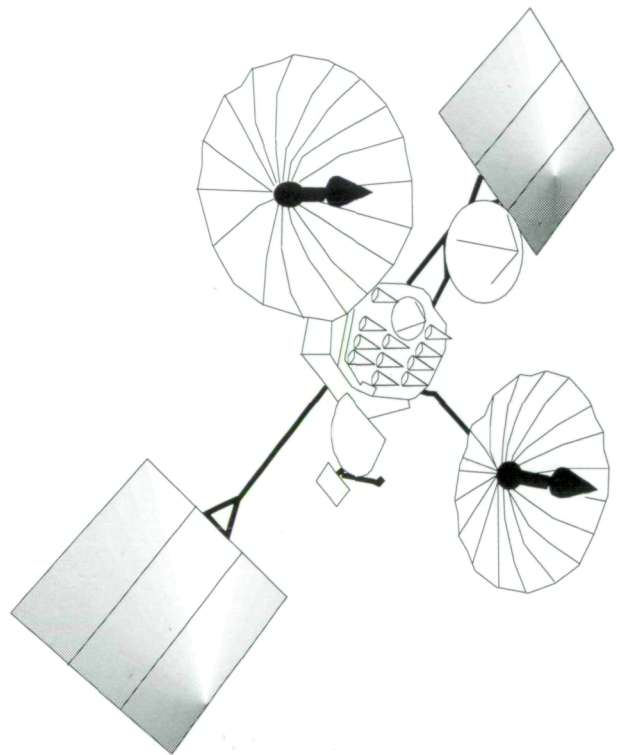
episode and also with current theoretical estimates of the length of a comet shower. It may well be that only one large impactor was responsible for devastating the environment in the case of a major extinction event. However, the accumulation of small environmental disruptions by a succession of minor impacts possibly could have led to the kind of limited extinctions seen near lesser-stage boundaries. The long-suspected roles of flood basalt volcanism, explosive volcanism, climate deterioration, sea-level change, and ocean-chemistry imbalances in accounting for the stage boundary extinctions are also potentially important, and would have to be integrated into the impact scenario if the derived correlation continues to stand up to further testing.

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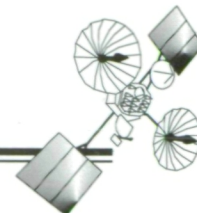
NETWORKS, PLANNING, AND INFORMATION SYSTEMS



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Space Views, a 3-dimensional visualization tool, helps mission operators understand their spacecraft status through simultaneous displays of spacecraft position, attitude, and instrument fields-of-view, chosen from a variety of options. Here, a Compton Gamma Ray Observatory (CGRO) operator is monitoring (clockwise from upper left) CGRO's orbital position, attitude relative to Earth, view seen by its Fine Sun Sensor, and view seen by its Fixed Head Star Trackers. In the latter display, the small rectangles are star tracker entrance apertures; lavender shading indicates they are closed to avoid contamination from the bright Earth (purple) seen in the background.



NETWORKS, PLANNING, AND INFORMATION SYSTEMS

SEVERAL GSFC organizational entities—most notably the Mission Operations and Data Systems Directorate (MO&DSD)—support varied and comprehensive programs of research and development to reach their operational objectives. The MO&DSD provides the end-to-end system support and operational infrastructure required for near-Earth, unmanned scientific spacecraft missions. Other entities support similar activities for missions that come under their purview. At one end of this operational “megasytem” is the spacecraft, with subsystems to be monitored and commanded, and the equipment and experiments needed to support the science agenda for the mission. At the other end is the flight operations team, responsible for the health and safety of the spacecraft, and the scientists, who are responsible for conducting the scientific investigations and interpreting the science data. To provide this complex suite of support activities, the MO&DSD daily engages in: (1) planning, designing, developing, and operating the spaceflight tracking and communications networks, and data systems support for spaceflight missions; (2) mission planning and analysis, space and ground network operations, spacecraft and payload command and control, flight dynamics, information processing, and flight operations; (3) planning and applied research and development of advanced data and telecommunications systems to support spaceflight missions; and, (4) maintenance of the space and ground communications networks, mission analysis and support computing capabilities, and the end-to-end data systems needed to meet mission support requirements.

The articles in this section give insight into some of the outstanding research and development work being carried on in the areas of communications and networking, advanced mission operations, data distribution, software and systems engineering, and planning and scheduling.

The *Communications/Networks* subsection contains five articles. The “VMEbus-Based Nascom Block Error Detector” (VME BED) article addresses the important question of data quality, and describes how this very important function is accomplished. “Demand Access Communications for Tracking and Data Relay Satellite System TDRSS

Users” explores the issues associated with providing TDRSS resources in a novel way. Currently these services are provided through prior scheduling based on estimates of user needs and mission event timelines. This article examines the possibilities of providing the required TDRSS resources on a demand basis to a defined group of missions. The “TDRSS Support for NASA Research Aircraft” article presents a system-level design for a radio-frequency (RF) communications capability between NASA research aircraft and the TDRSS. This innovation will be required to support a true telescience capability between ground operations and the aircraft. “CCD (Charge-Coupled Device) Integrated Receiver Prototype” addresses research that is being successfully conducted to provide NASA with the high degree of communications flexibility, automation, and power and size reductions required for future communications needs. Finally, the “Automated Ground Network System (AGNS)” article reviews current activities needed to bring a new level of automation to the ground network systems at Merritt Island, Florida, and Bermuda.

The four articles in the *Support for Mission Operations* subsection give some interesting insights into the innovations that are being introduced into mission operations. “Practical Application of Real-Time Distributed Processing Concepts on the HST Ground System” gives details about the support necessary for this complex mission. The “Solar and Heliospheric Observatory (SOHO) Near-Real-time Commanding Process” article discusses the exciting prospects for real-time command of spacecraft instruments by scientists reacting to real-time (and perhaps unanticipated) scientific opportunities. In “Advancing Satellite Operations with Graphical Expert Systems,” we are introduced to innovations involving the expert system development environment called GenSAA (Generic Spacecraft Analyst Assistant). GenSAA is providing resource (time, money, personnel)-effective methods for developing and deploying state-of-the-art expert systems in all phases of mission operations. Finally, “Space Views” briefly introduces the object-oriented graphical approaches that will support 2-D and 3-D displays of information required by flight operations teams to under-

stand the dynamics of changing spacecraft states as missions proceed.

The *Data Distribution* subsection has five articles. "IPD's Data Distribution Facility" presents a description of how the DDF handles delivery of the Information Processing Division's (IPD) products to its customers. The following three articles come from the Earth Sciences Directorate (Code 900). "The Goddard Distributed Active Archive Center Version 0 System" addresses the status of this proof-of-concept component for NASA's Earth Observing System DAAC, being developed at GSFC. Another prototype is discussed in the "Tropical Rainfall Measuring Mission Science Data and Information System." Missions that will generate large volumes of data will benefit from the work presented in "Near- Real-Time Generation of Browse Products for Terabyte-Sized Databases." Space-looking spacecraft are also dealt with in this section, with a discussion of the requirements and implementation of techniques for "ROSAT Data Processing and Archiving."

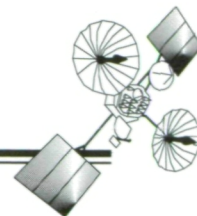
The five articles in the *Advanced Software and Systems Engineering* subsection introduce some of the technological innovations that demonstrate the robust infrastructure of the MO&DSD organization. "Reuse on the Large: Utilizing the Evolutionary Domain Life-Cycle Model with a Knowledge-Based Approach" addresses the advances being made in software and system reuse. The Knowledge-Based Software Engineering Environment (KBSEE) discussed in this article is a successful prototype system to generate and tailor reusable artifacts. "Reusable Software Components for Monitoring and Control of Telemetry Processing Systems" focuses on the reuse of software components designed for controlling and monitoring the operation of very large scale integration (VLSI)-based

systems for telemetry processing. The "Distributed Computing Initiative" article addresses issues associated with the development, testing and control of distributed open systems. It focuses on two innovations: the Distributed Applications Monitor tool (DAMT), and the Distributed Process Control Program (DPCP). "Ground Operations Technology Testbed" introduces the reader to the GOTT, which is designed to support the infusion and evaluation of emerging technological developments that could play an important role in the future of the MO&DSD. Concluding this subsection is "Flight Software for the Coprocessor, HST's New On-Board Computer," which discusses a new Central Processing Unit (CPU) and new memory designed to mate to an existing flight computer during the Hubble Space Telescope Servicing Mission.

The final subsection, *Planning/Scheduling* contains three articles. "EOS Distributed Planning and Scheduling Prototype" discusses the prototyping task to evaluate planning and scheduling operations concepts for the Flight Operations Segment (FOS) of the EOS Data and Information System (EOSDIS). A discussion of requirements and implementation of techniques necessary for, e.g., SMEX planning, is found in "Science Planning Goes Online." The "Request-Oriented Scheduling Engine (ROSE)" article discusses the innovations associated with "flexible scheduling." It currently exists as an operational prototype, and is scheduled for proof-of-concept application in the Network Control Center (NCC).

Continued advancements in these and other areas of research and development will significantly contribute to GSFC's success in meeting the challenges of mission operations in this decade and into the 21st century. Please read on!

Walter F. Truskowski



COMMUNICATIONS/NETWORKS

VMEBUS-BASED NASCOM BLOCK ERROR DETECTOR

THE PURPOSE of the VMEbus Block Error Detector (VME BED) is to monitor data quality of 4,800-bit Nascom blocks on a RS-422-A communications line. Each VME BED can simultaneously monitor (in parallel) either simplex side (send/receive) of a Nascom communication line. Simplex side selection (send/receive) and normal/reversed timing selection are done by the user.

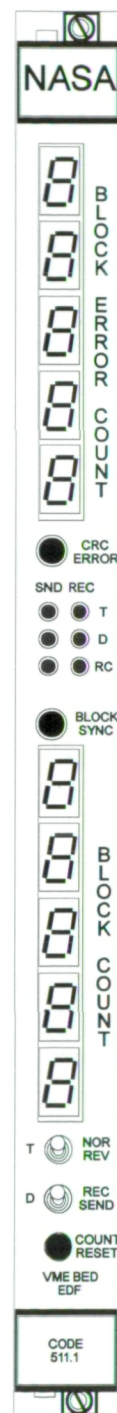
Upon reception of a Nascom block on the monitored communications line, the block sync light-emitting diode (LED) will briefly illuminate and the block count will increment. If the received Nascom block has an incorrect 22-bit cyclic redundancy check (CRC), the CRC error LED will briefly illuminate and the block error count will increment. The VME BED can count up to 99999 detected Nascom blocks and up to 99999 detected Nascom blocks with CRC errors. Each counter has an overflow indication. Previous designs used off-the-shelf transistor-to-transistor logic microcircuits requiring about 40 microcircuits per BED board. The 10:1 attenuated patch panel added additional cost to the troubleshooting procedure and added another piece of equipment which could fail during troubleshooting. Another limitation was the inability to count the number of Nascom blocks detected and a limited number (999) of blocks detected with CRC errors. In contrast, the VME BED design is based on one programmable logic device. A few additional integrated circuits are used for the Nascom line interface and the front panel display interface.

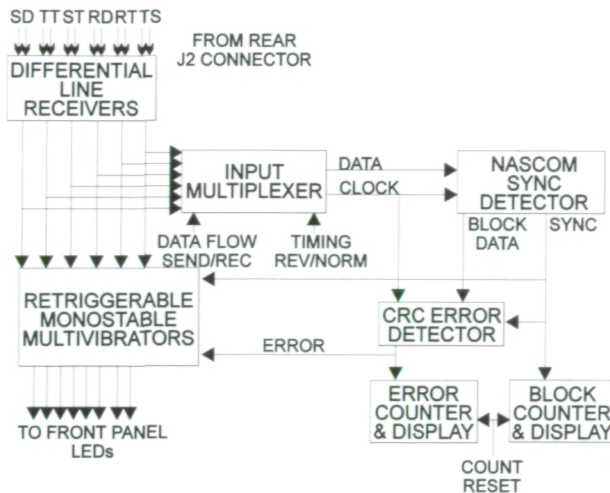
The VME BED is capable of monitoring either data flow of a full-duplex Nascom communications line. The VME BED is a standard 6U, 160-mm single-slot VMEbus card for mounting in any standard VME chassis. The front panel display (shown in the first figure) contains the operating controls, LED indicators, switches, block count display, block error count display, ejector handles, and mounting screws necessary to the operation and testing of each full-duplex port.

The selection of the data signals upon which to perform error detection is controlled at the front panel display. This block counter function and the block error detection function are performed by the following sequence of events:

- The standard 24-bit Nascom block synchronization pattern, 627627 hexadecimal (h), is detected;

VME BED.





Block diagram of VME BED circuit.

- The block sync LED is briefly illuminated and the block count is incremented;
- The CRC calculation is performed on the data field by the CRC generation circuitry. The P1 and P2 flag bits are not included;
- After the block CRC is encoded, a bit-by-bit comparison is performed on the CRC value located in the last 22 bits of the Nascom block;

- Finally, if the comparison fails, the block error count is incremented, and the block CRC LED is briefly illuminated.

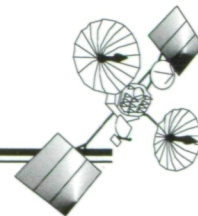
The circuitry that performs the CRC calculation is summarized in the block diagram in the second figure.

The VME BED can be used to monitor data quality and connectivity of Nascom line switching systems. It can also be used to monitor data quality (as a control) for equipment that can send and/or receive Nascom blocks. This controlled monitoring has proven extremely useful in operational and testing scenarios.

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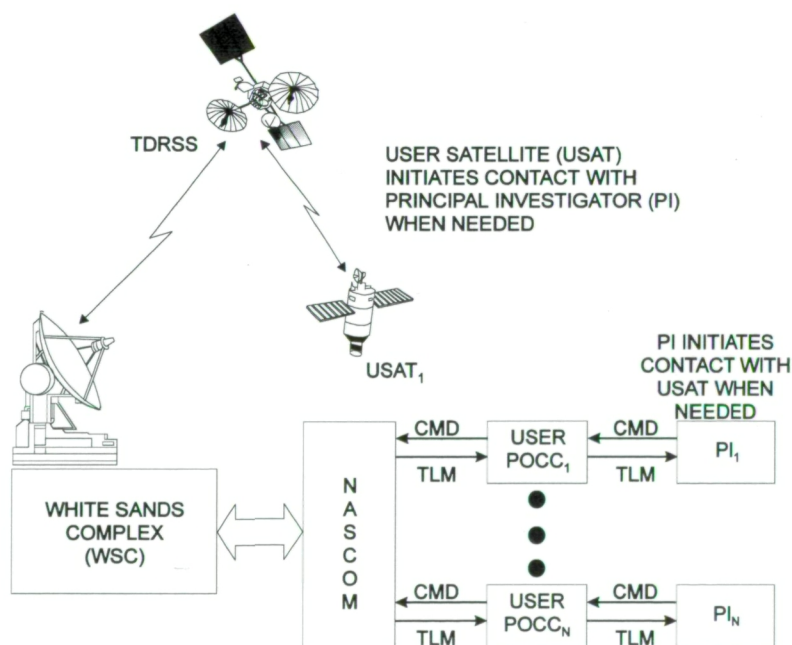
DEMAND-ACCESS COMMUNICATIONS FOR TRACKING AND DATA RELAY SATELLITE SYSTEM USERS

THE TDRSS has long been used to provide reliable low- and high-data-rate communications relay services between user spacecraft in Earth orbit and the ground. Users of TDRSS relay services include the Space Shuttle and unmanned missions such as Landsat and the Hubble Space Telescope (HST). To date, these TDRSS services have been implemented via prior scheduling based upon estimates of user needs and mission event timelines. While this approach may be necessary for large users that require greater amounts of TDRSS resources, TDRSS can potentially offer the planned community of smaller science missions the unique opportunity for services-on-demand. In particular, the TDRSS Multiple Access (MA) service, with its phased-array antenna and Code Division Multiple Access (CDMA) signal structure, could be used to implement a true demand-access capability.

A primary goal of the ongoing effort is to use the *existing* TDRSS resources (both in space and on Earth) in new ways, providing increased benefits to the user community. Potential operational uses of this new capability include: nominal user command and telemetry; rapid, unscheduled transmission of anomalous conditions by user

satellites; rapid reaction to unplanned mission events or targets of opportunity; and rapid handover to scheduled service when needed. Approaches that provide significant benefits to the TDRSS (via increased system utilization or simplified operations) have been examined during the past year and are discussed here.

Demand-access services have potential application to both the TDRSS forward- and return-communications links. For forward- (command) link communications, the Principal Investigators (PIs) for each mission could initiate communications with their spacecraft via service requests and command messages sent through TDRSS via the White Sands Complex, as shown in the figure. By eliminating the need for prior service scheduling, demand-access capability would permit such forward-link interactions to occur whenever necessary. Benefits include increased PI access to their spacecraft, and simplified network operations through increased automation of operations. For short-duration contacts that do not require excessive TDRSS resources, demand-initiated services could replace the current approach, which is based on prior service scheduling.



TDRSS forward and return demand-access service.

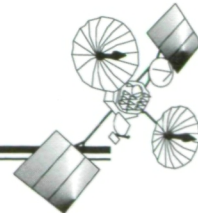
A return-link demand-access capability allows a user spacecraft to initiate service and data return with the ground whenever necessary via messages and service requests sent through TDRSS. While demand-access return service could be used for such routine operations as command acknowledgments or echoes, there is also potential for real-time reaction to time-critical events, such as unplanned science opportunities or spacecraft anomalies.

Two designs have been formulated as implementations of a forward-link demand-access capability using TDRSS MA services. In the first approach, short messages to the user satellites are transmitted during gaps in the existing MA forward-link service schedule. The process begins when the PIs on the ground format and send service requests to the White Sands Complex. At White Sands, these service requests are buffered until gaps suitable for DA service become available in the planned MA forward schedule. When a forward link becomes available, the TDRSS and ground equipment are automatically configured for service to the desired user satellite and the forward-link message is transmitted. The user satellite, which keeps its receiver on at all times, acquires and demodulates the forward link, then sends message confirmation on the demand-access return link. Service set-up and message transmission in this demand-access approach are identical to the current MA forward-link communications implementation, so a minimum of new hardware and software are required. While some software modification is required at White Sands to implement the message buffering and demand-access service set-up functions, the approach uses the existing TDRSS satellites and is compatible with existing TDRSS MA users. The design relies on gaps in scheduled service for demand-access message transmission, so message throughput is a function of service loading for the scheduled MA forward-link users. Preliminary estimates of MA forward-link utilization have indicated that gaps in the forward service schedule suitable for demand-access service should occur sufficiently often to permit demand-access message transmission with a minimum of delay.

The second forward-link demand-access design relies on a time-hopped, MA-forward antenna beam when no other MA-forward services are needed. Here, ground-controlled beamforming is used to steer the TDRSS MA array through a fixed pattern of 8 to 12 beam locations, or cells, covering part or all of the Earth's sphere as seen from TDRSS. As before, the PIs format and send messages to

White Sands, but in this case the messages are in the form of frames with a common format and length for all users. The common message formats allow White Sands to multiplex the forward frames for all users onto a single time division multiplexed data stream. The entire message sequence (containing 10 to 20 short messages) is then sent to each MA forward-cell in turn. The user satellites again keep their receivers on at all times, demodulating the MA-forward link whenever it becomes available. In this approach, the user satellites must also demultiplex the MA-forward message sequence to eliminate all undesired forward-link messages. As before, message confirmation by the users' satellites can be accomplished via the demand-access return link. Service set-up and message transmission in this demand-access approach differ significantly from the current MA-forward-link communications implementation. Because a common forward channel is shared by all user satellites, the user satellites must share a common pseudonoise (PN) sequence for the demand-access channel, switching to their user-unique sequence when normal (scheduled) services are required. Additionally, each user satellite needs to compensate for TDRSS Doppler shifts, since frequency compensation of the common forward-link is not possible from the White Sands transmit side. Against these factors, the scanning beam design offers the potential for higher demand-access message throughput as compared to the first design described above. Also note that receiver technologies and designs applicable to the user satellites are currently under examination in other GSFC studies. Selection among the two candidate forward-link demand-access designs will depend on detailed system analyses now under way.

The return demand-access design relies upon the unique TDRSS capability for ground-based beamforming at White Sands to achieve the desired coverage. Using multiple beamformers/receivers at White Sands allows formation of multiple, simultaneous MA return antenna beams with existing TDRSS satellites. Using 10 to 15 antenna beams, coverage is provided for almost all low-altitude positions visible to a single TDRSS satellite. User satellites access the demand-access return link by transmitting 5- to 15-second message packets whenever there is line-of-sight visibility to TDRSS. At White Sands, the received message packets in each return beam are acquired and demodulated. The user satellite transmitting each message is identified and, in turn, each message is routed to the appropriate PI.



Using multiple antenna beams and receivers, many random-access users can be simultaneously accommodated with negligible probability of contention. Nevertheless, in case of packet collisions, various protocols for return-packet transmission can be used to resolve contention. Minimum complexity is achieved via an ALOHA implementation, in which there is no user coordination of return packet transmission timing. This results in a higher probability of contention, yet may be acceptable due to the inherent robustness of the architecture. As in the forward demand-access design, the return design relies on the existing TDRSSs to provide a new service capability. The primary impact to the White Sands Complex is the need for added beamformers and receivers to implement the demand-access services. This impact is an incremental increase to the existing ground-station capability; no new technologies are required.

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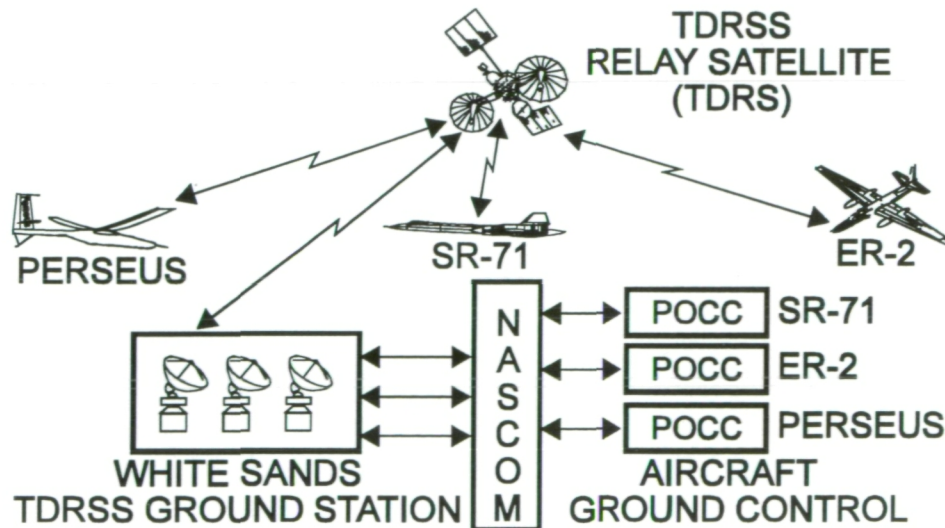
TRACKING AND DATA RELAY SATELLITE SYSTEM SUPPORT FOR NASA RESEARCH AIRCRAFT

TO EXPAND the efficiency and flexibility of NASA research aircraft programs, particularly those for the ER-2 high-altitude research, the unmanned Perseus, and the SR-71 supersonic research, a systems-level design to provide radio-frequency (RF) communications capability between NASA research aircraft and NASA's TDRSS has been initiated. The goal of this airborne satellite communications (satcom) capability is to realize telescience potential by utilizing NASA's Space Network (SN) to relay data and commands between the aircraft and a ground-based control center, as shown in the figure.

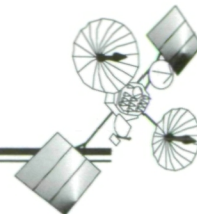
The fundamental mission requirements for each of the three aircraft types are presented in the table. Along with their unique payload accommodations, these mission requirements result in distinct design and operational solutions. To develop cost-effective designs, a detailed assessment of applicable and available technology was conducted in the areas of antenna systems, aeronautical radomes, high-power amplifiers (HPAs), speech compression, and TDRSS satcom transponders. The focus of the design studies in 1993 has been the SR-71 and the ER-2. In parallel with this effort, GSFC has been developing an experimental system to demonstrate a 10-kbps data rate for the airborne link between the Perseus and TDRSS.

Of the three aircraft under study, the SR-71 satcom design is by far the most challenging, as a result of its extreme operating conditions, its near-continuous and high-rate communications requirements, and its harsh payload accommodation characteristics. Of particular note is its need for full coverage (i.e., no antenna blockage), while allowing the satcom payload not more than an inch of protrusion above the fuselage. This last constraint arises from the need to avoid any disturbance to the laminar flow around the aircraft which would alter the aerodynamics of the SR-71 and compromise its role as a hypersonic experimental platform.

The best solution is an antenna sitting several inches above the fuselage protected by a radome. Design studies have shown that a phased-array antenna fabricated on a ceramic tile can readily meet the communications and visibility requirements, but would require a radome height of 9 to 12 inches (in)—substantially exceeding the 1-in constraint. Based on these considerations, a viable approach is a dual antenna arrangement. The primary antenna is in the aircraft nose cone; the other is on the aft fuselage, and complements the nose cone antenna by providing visibility in regions blocked by the wings and tail. The nose cone can be fabricated to be RF transparent at a particular



TDRSS support for NASA research aircraft.



operating frequency, either S-band or Ku-band for TDRSS operations. In this way, the nose cone antenna easily provides below-the-horizon coverage. The reference design is a phased-array antenna with electronic steering in elevation and operating at Ku-band frequencies. The antenna is an inclined tile, ~3 in x 3 in, that sits on a turntable that is mechanically steered through a 360° azimuth. The required field-of-view for the aft antenna is relatively small, covering only areas blocked to the nose cone antenna; therefore it has a simpler design. Due to cabling losses, separate HPAs for each antenna will be needed; fortunately however, power consumption is not a problem for the SR-71. The proposed SR-71 TDRSS transponder is a modification of the balloon-class TDRSS transponder, developed by Stanford Telecommunications under the guidance of GSFC's Telecommunication Systems Branch and sponsorship of the Advanced Systems Office of Space Communications.

The ER-2 is a far easier problem to solve than that of the SR-71, both in terms of requirements and accommodation. An attractive approach is to employ an antenna/radome system located atop the fuselage just aft of the cockpit. The radome has already been designed by Lockheed, thereby allowing simplicity and cost savings. The antenna design is similar to the inclined tile, phased array implemented for the SR-71. The antenna is to oper-

ate at S-band frequencies, thereby accommodating: (1) S-band MA service for low-data-rate support most of the time, and (2) S-band Single-Access (SSA) service for periodic high-data-rate support. The potential for wing blockage at low elevation angles is now being analyzed, and is of particular concern when the ER-2 is operating from high latitudes, such as near the poles. However, this design should satisfy most of the requirements.

A second design approach is to place the antenna atop the aft stabilizer. This provides excellent visibility with minimal blockage, even at below-the-horizon pointing. There is, however, a 15-lb load limitation at this location, which is a key design driver. An antenna/radome combination design has been developed which appears capable of meeting the weight constraint and yet still provides the required gain and coverage. The remaining components of the ER-2 satcom system (i.e., transponder, HPA, and data subsystem) reside in a compartment at the base of the tail section. As with the SR-71, the balloon-class TDRSS transponder will be used for the ER-2. For the ER-2, output power adjustment for MA and SSA services is a new feature and must be added.

These designs represent relatively straightforward extensions of current, available technology. Little modification is required by the current SN to accommodate this new

NASA Aircraft Needs and Impact

PARAMETER	SR-71	ER-2	PERSEUS	IMPACT
Geographical Location	- Continental US - Mostly west of Texas - Expansion to Other Areas	- Global coverage - Polar missions	- Global coverage - Polar missions	- TDRSS ZOE: Indian Ocean region and polar regions - Possible Backside TDRS - High lat and near-ZOE lon causes low elevation angles
Return Data Rate	300 Kbps; Min. 1 Mbps; Max.	50 Kbps - Up to 3 Mbps (Option)	50 Kbps	Above 50 Kbps, must use Single Access (SA) Service
Forward Data Rate	Digital Voice: <10 Kbps	Digital Voice + Commanding: <10 Kbps	Commanding (<10 Kbps)	Multiple Access (MA) Service possible if <10Kbps
Service Contacts	Continuous throughout Flight	- Near-Continuous low rate - Periodic high rate	Near-Continuous	Long duration SA service hard to get
Link Dropouts	Minimize; None desirable	Occasional acceptable	Occasional acceptable	Aircraft blockage is prime concern
Banking Angles	±45°; desirable ±5°; acceptable	±5°	±5°	Exacerbates elevation angle requirements

class of users. The results of this study will be used to develop system design specifications, and will eventually result in hardware development.

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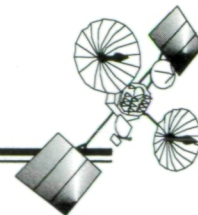
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Dr. Ted Benjamin is a project manager with Stanford Telecommunications, Inc. (STI). He has been supporting GSFC in TDRSS and TDRS II efforts for 14 years. In the past several years, his work has been particularly focused on advanced receiver design for both ground and space applications. He holds a PhD in Electrical Engineering from Cornell University.

Mr. George Kossakes is a systems engineer with Stanford Telecommunications, Inc. He has been supporting GSFC for TDRSS communication links with NASA high-altitude research aircraft. He has been working with satellite communication systems at COMSAT, Computer Sciences Corporation, and American Satellite Company for the past 25 years. Mr. Kossakes earned his BS and MS degrees in Electrical Engineering from George Washington University.



CHARGE-COUPLED DEVICE INTEGRATED RECEIVER PROTOTYPE

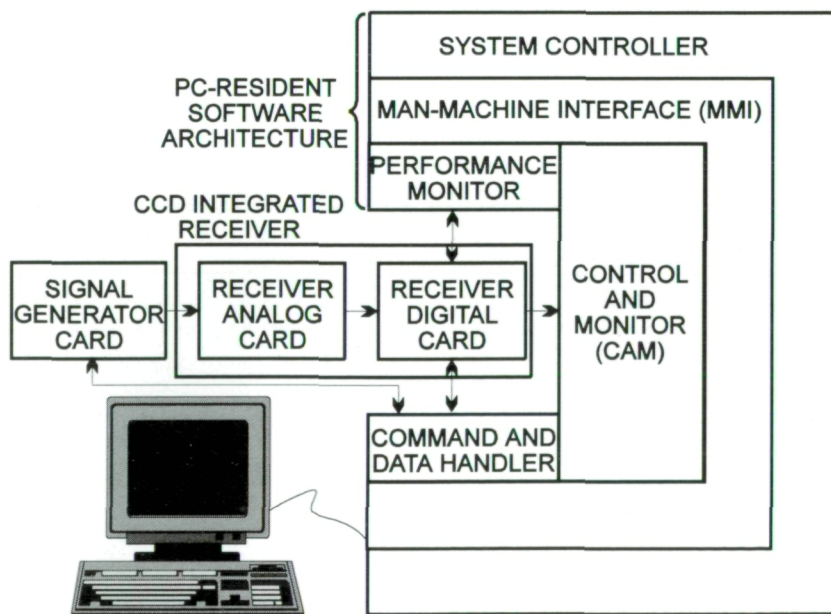
IN ANTICIPATION of future requirements by both space and ground systems for a high degree of communications flexibility, automation, and power and size reduction, for the past 2 years Code 531 has sponsored advanced receiver research and development. This initiative has led to the development of a laboratory prototype called the Charge-Coupled Device (CCD) Integrated Receiver Prototype.

As its name implies, the receiver's key attributes are its use of CCD technology and an architecture that integrates the receiver's signal processing functions. The CCD technology employed (and developed under NASA's sponsorship) is MIT Lincoln Labs' latest programmable analog correlator chip, the 2-ATC CCD, which serves as the receiver's PN-code matched filter for despreading and filtering operations. This particular CCD chip contains two full-length 512-stage, 256-tap correlators and two 24-stage, 12-tap companion correlators. A quasi-analog device, the CCD correlator chip performs signal correlation in the analog domain at digital domain-equivalent rates exceeding 10 billion multiply-accumulate operations per second when clocked at 40 MHz—all the while consuming less than 1 watt. Within a signal processing environment, the computational capability of the CCD may be

used to great advantage to add tremendous signal processing capacity to receiver architectures designed to exploit its strengths.

The CCD Integrated Receiver prototype system is a state-of-the-art system employing novel architecture and advanced technology to provide extensive capability in a compact package. The design of the receiver has evolved from earlier efforts to develop an S-band beacon receiver prototype system for the Advanced Tracking and Data Relay Satellite. Through judicious use of the CCD and other key technologies, it has been possible to design the prototype to operate both as a user (forward-link) and a ground-based (return-link) receiver to support TDRSS and Ground Network (GN) links for both normal user and Shuttle services. The basic elements of the prototype receiver system architecture are: the System Controller, the Signal Generator Card, and the CCD Integrated Receiver. The interrelationships between these functional blocks are depicted in the figure.

The receiver portion is composed of two cards: the Receiver Analog Card and the Receiver Digital Card. Both cards follow the same form factor as the Signal Generator Card. The Analog Card accepts IF inputs centered at 70



The receiver is composed of two cards: the receiver analog card and the receiver digital card.

MHz, and therefore may be directly connected to the Signal Generator Card during engineering and integration tests. Circuitry on the card then conditions and downconverts the signal. For PN-spread signals, the resultant baseband waveform is sent to the CCD correlator for removal of PN codes (despreading) prior to digitization; for non-spread signals, downconversion is done to a secondary IF where it is subsequently sampled at IF and sent to the CCD for demodulation. The Digital Card accepts the 8-bit digital signals from the Analog Card and processes them to acquire and to track the received signal.

Digital signal processing (DSP) within the CCD Integrated Receiver is performed primarily by three Motorola DSP96002 processor chips located on the Receiver Digital Card. Each of the three signal paths within the receiver is assigned a processor; one processor is defined as the master and the remaining two, as slaves. Together, these processors execute all algorithms necessary to perform signal acquisition and tracking. Each processor operates on a 37.5-MHz system clock, resulting in an aggregate instruction execution rate of 56.25 million instructions per second (MIPS) for the Digital Card. The use of such a processor-based design has resulted in a very powerful and flexible system design for signal processing applications.

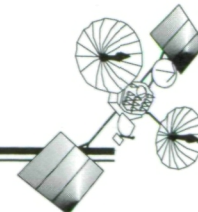
During the past year, the power and flexibility of the receiver architecture has been demonstrated in a variety of operational modes. The receiver has demonstrated support for a TDRSS forward-link, with data rates from 125 bps to 64 kbps. Using the parallel processing capabilities of the CCD correlator and the highly integrated receiver architecture, PN acquisition was achieved in less than 1 second. This performance represents a marked improvement relative to today's receiver performance of 20 seconds or more. Equally efficient, rapid carrier acquisition is achieved in under 1 second using a fast Fourier transform (FFT)-based carrier acquisition algorithm. Additionally, support in handling GN uplink signalling was also demonstrated at a command data rate of 2 kbps. Characteristics of the GN uplink signal are an unmodulated carrier with a phase-modulated, 16-kHz subcarrier containing uncoded phase-shift keyed (PSK) data.

Also in the past year, support for Shuttle modes was added to the receiver's capabilities. Although not originally designed to support the link, Shuttle support was devel-

oped for the Manchester-formatted signal at rates of 288 kbps and 576 kbps. The feasibility of the addition demonstrates the flexibility and power of a processor-based receiver. In this application, the CCD stripped the Manchester-coding and demodulated the signal at data rates that otherwise would have been prohibitive for the DSP acting alone.

Using the technique of quadrature IF-sampling, the receiver is capable of processing and demodulating binary PSK (BPSK) signals with data rates ranging from 125 bps to 64 kbps using both the full-length and companion CCD correlators. At higher data rates, it is necessary to use only the CCD's shorter companion correlator to maintain the CCD sampling rate under 10 MHz. In quadrature IF-sampling, the receive signal is sampled directly by a single analog-to-digital (A/D) converter and at an intermediate frequency, rather than at baseband using dual A/Ds as in the conventional approach to signal processing. By choosing an appropriate sampling frequency and by taking advantage of signal aliasing, the quadrature IF-sampled signal may be treated as a baseband-sampled signal. An obvious benefit of this technique is the reduction in the component count needed to support an additional mixing stage and further reductions in system size, power, and weight. Furthermore, implementation complexities typically associated with baseband sampling, such as DC-biased mixer output and imbalances in phase and frequency, are avoided.

In a novel application of the IF-sampling and the CCD correlator technologies to analog signals, the receiver capability was extended to include processing and demodulation of a conventional FM signal. FM is a mode supported by GN ground stations to handle Shuttle video. In the demonstration, a 20-kHz-bandwidth musical program was frequency-modulated on a carrier frequency of 70 MHz. The signal was then directly connected to the Receiver Analog Card where it was quadrature-sampled at an intermediate IF using the CCD. Frequency discrimination was performed on the basis of the quadrature-sampled signal, and the original baseband program was digitally reconstructed to 8 bits. Finally, the reconstructed signal was transferred from the Receiver Digital Card to a personal computer where a commercially available soundboard replayed the material. Without further refinement to the frequency discriminator algorithm, the quality of the reconstructed audio was deemed suitable for voiceband application.



In the 2 years that NASA has sponsored development of the CCD Integrated Receiver, it has been demonstrated that it is possible—utilizing the state-of-the-art in signal processing technologies, including high-performance DSPs and CCDs—to develop powerful and flexible receiver architectures that are suited to a wide variety of NASA and commercial applications. Already, the compact, two-card receiver system allows placement of up to ten individual receivers within a single 19-in rack-mountable chassis. In addition, analysis of the receiver design has shown that further reductions in size and power are possible. The focus of current research activity extends to potential applications to other NASA initiatives such as the Gamma Ray Observatory (GRO) Remote Terminal System (GRTS) and Automated Ground Network System (AGNS).

This work was done with the invaluable support of Stanford Telecommunications' Advanced Technology Laboratory, which is currently developing the CCD Integrated Receiver.

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Mr. Thomas Land is a Lead Design Engineer in Stanford Telecommunications' Advanced Technology Laboratory, which is currently developing the CCD Integrated Receiver. He earned a BS in Electrical Engineering, a BS in Computer Science, and a BA in Biology from Washington University in St. Louis. Mr. Land has supported GSFC prototyping and hardware evaluation for 5 years.

THE AUTOMATED GROUND NETWORK SYSTEM

NASA's GN for spacecraft control and communications has evolved gradually over the years to satisfy changing requirements and to accommodate new technologies. It has effectively satisfied mission requirements and has generated an enviable record of station availability and performance. However, the evolutionary process has resulted in a diverse collection of aging, custom equipment that is becoming increasingly more difficult and expensive to maintain. Technology advances over the past few decades now allow for better, faster, and cheaper ground tracking stations. The goal of the Automated Ground Network System (AGNS) project is to use these advances to implement dramatic improvements in station operating costs and efficiencies.

The existing stations' architecture is tightly coupled. Changes in one subsystem often impact equipment and procedures elsewhere on the sites. This necessitates extensive regression testing when making software modifications. Additionally, since the station equipment uses a variety of custom communications interfaces and protocols rather than interfaces based on internationally recognized standards and protocols, it is difficult to use commercial off-the-shelf (COTS) equipment for system upgrades. This increases development effort, complexity, and cost. A further consequence of low levels of interoperability is that subsystems often are replaced on a one-for-one basis, perpetuating the problem. Since operations costs are driven primarily by peak staffing loads, the lack of interoperability between station equipment and between operator interfaces, the lack of centralized monitor and control capabilities, and the lack of automation technology are all major cost-drivers at the sites.

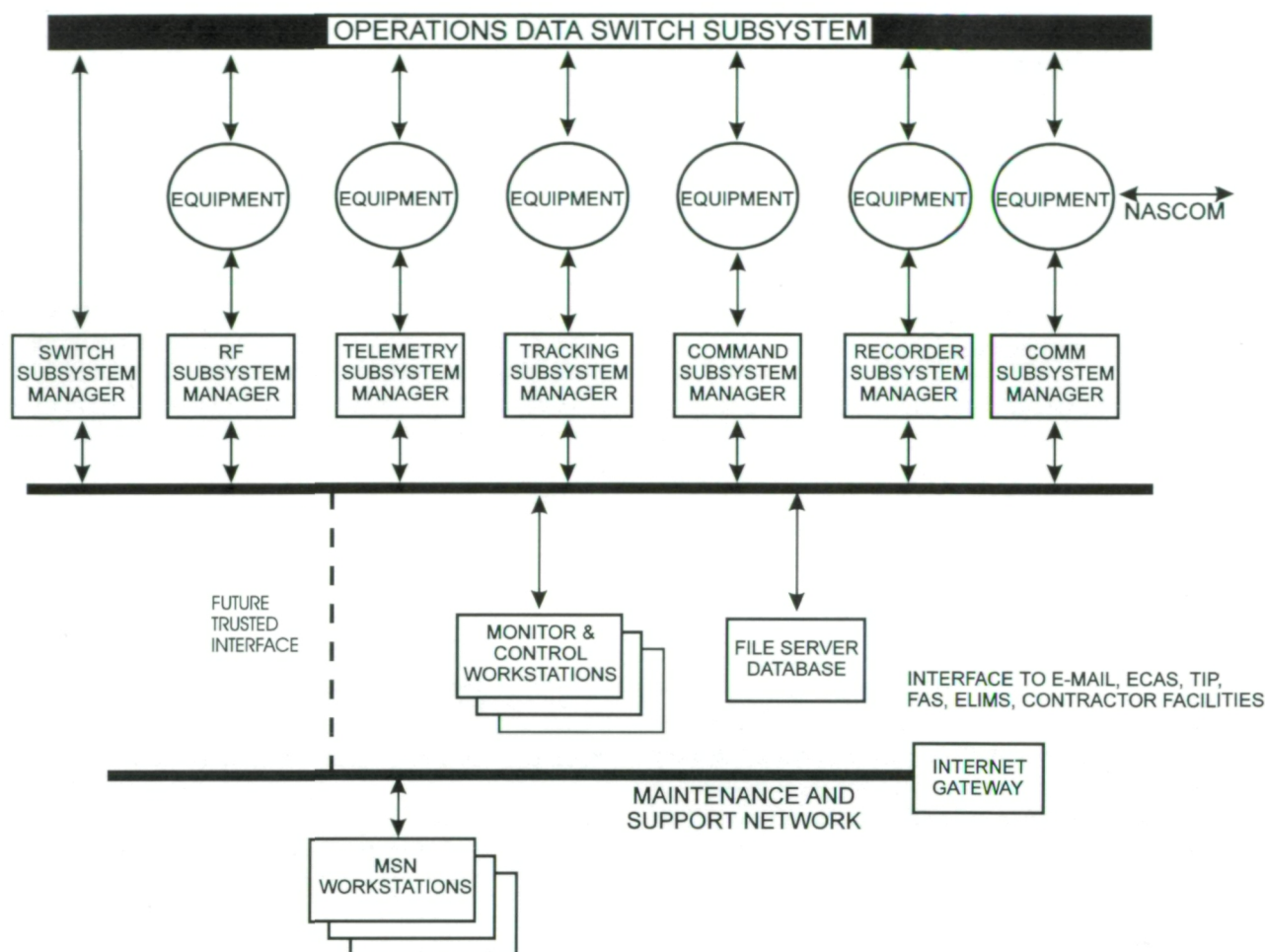
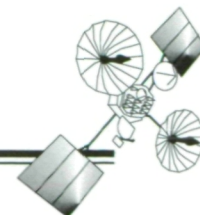
The AGNS project, managed by the Telecommunication Systems Branch (Code 531) at GSFC, will enable more cost-effective GN tracking station support at Merritt Island, Florida, and Bermuda. The objectives of the AGNS project are to:

- Significantly reduce station life-cycle costs by automating station configuration, testing, fault detection and recovery; by centralizing monitor and control capabilities to allow operation with fewer operators; and by providing remote monitoring and analysis capabilities to reduce travel of contractor maintenance personnel to the stations, and to improve response time when problems do occur.

- Improve station reliability and availability by replacing aging custom equipment with more modern and reliable COTS technology; by utilizing expert systems to capture operator knowledge, filter display information to avoid operator overload, and to respond to contingencies; and by facilitating quick, on-line access to all centralized Spaceflight Tracking and Data Network (STDN) technical information and management information systems.
- Enable and enforce use of internationally recognized communications standards and protocols such as the International Standards Organization/Open Systems Interconnection (ISO/OSI) protocols; the Government Open Systems Interconnection Profile (GOSIP); and the Consultative Committee for Space Data Systems (CCSDS) telemetry and command protocols.
- Provide a flexible station architecture that can readily accommodate future requirements and technology with minimum effort and cost by maximizing the use of COTS equipment; by applying object-oriented design and implementation methodologies to the station hardware and software architectures; to utilize resource editors and commercial databases to create, modify, and store parameters rather than embedding these parameters in the software; and by defining, documenting, and imposing interface monitor and control specifications for all future GN equipment upgrades.

The AGNS project plans to implement these objectives through three main subprojects: the AGNS Development Facility (ADF), the AGNS Maintenance and Support Network (MSN), and the AGNS Monitor and Control Subsystem (MCS). The ADF will provide developers with the tools necessary to prototype, develop, test, and maintain other subprojects in support of the system. Station personnel will share these tools via wide area networks (WANs) to enable their early participation in system requirements analysis and design. Activities in 1993 supporting these objectives included overall system design, selection of COTS components, and development of prototype systems.

As seen in the figure, the MSN will consist of a number of workstations connected by an Ethernet local area network (LAN) to an Internet gateway. This gateway will



AGNS Architecture.

provide effective electronic connectivity for electronic mail services, operations and maintenance support, and for seamless integration with major Networks Division (Code 530) Management Information Systems: the Technical Information Program (TIP), the Engineering Change Automation System (ECAS), the Facilities Automation System (FAS), and the Enhanced Logistics Information Management System (ELIMS). For security reasons, the MSN will not be connected to the MCS network until a trusted interface is identified or developed. The MCS will provide centralized monitoring and control of all station subsystems. The design uses an object-oriented approach to hide subsystem complexity from operators. As seen in the figure, the MCS is composed of a file server/database, a series of distributed subsystem managers, a small number of centralized monitor and control workstations, and an Operations Data Switch Subsystem, all interconnected via a communications network using standard com-

munications protocols. The database stores important subsystem equipment configuration parameters for all supported spacecraft, as well as the station's mission support schedule. The subsystem managers encapsulate the details of the individual subsystem components, provide well-defined monitor and control interfaces, and utilize expert systems to help automate subsystem configuration, testing, fault detection and recovery.

The subsystem managers monitor and control their subsystem components via a real-time database. The real-time database functions as a presentation layer between operator workstations and equipment. It provides status information to the centralized monitor and control workstations, which display the status using a standard graphical operator interface. These workstations also transmit control information, via the real-time database, to the subsystem managers.

The system schedule defines overall operations requirements. The subsystem managers decide locally how to implement those portions of the schedule that they can accommodate. During equipment configuration and fault recovery operations, subsystem managers transmit status messages to the Switch Subsystem Manager. This manager connects the subsystem processing strings together in accordance with the system schedule, using the Operations Data Switch Subsystem. A detailed record of all configurations is maintained for subsequent fault or performance analysis, should this be necessary.

This object-oriented architecture reduces the amount of coupling between subsystems and creates a hierarchical monitor and control design structure. In a typical operations scenario, the schedule, which is a high-level document, will be received at the AGNS station from the Network Control Center (NCC). This schedule will be stored in a site database where it will be accessible to each of the subsystem managers. Each subsystem manager will query the database using a structured query language (SQL) protocol to obtain relevant portions of the schedule. Each manager will know from its local knowledge base, the necessary frequencies, bit rates, and other configuration parameters required for its subsystem to satisfy its specified support functions or requirements. The managers will then allocate resources to each function. Subsystem managers are aware of the status and allocation of all components they control, and they are locally responsible for resource allocation. Status information is available to external subsystems if desired, but this information must be requested from the manager.

At the requested time of support, each subsystem manager will read its schedule requirements from the central

database, will allocate and test subsystem components, and will send a status message to the Switch Subsystem Manager informing it of which subsystem components it is contributing to the overall processing string. The Switch Subsystem Manager will use this information to control the actual data paths in the Operations Data Switch Subsystem.

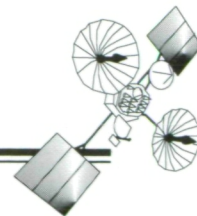
Although the AGNS project will provide the GN with a new infrastructure that will enable life-cycle costs to be significantly reduced, these cost reductions cannot be fully realized until the old, custom equipment is replaced with new, standard equipment. The Telecommunication Systems Branch has already developed plans to replace this equipment over the next few years. A better, faster, and cheaper GN should soon be a reality.

This work was done in collaboration with Mr. Peter N. Militch, a project engineer with AlliedSignal Technical Services Corporation.

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SUPPORT FOR MISSION OPERATIONS

PRACTICAL APPLICATION OF REAL-TIME DISTRIBUTED PROCESSING CONCEPTS ON THE HUBBLE SPACE TELESCOPE GROUND SYSTEM

DISTRIBUTED PROCESSING has become a fundamental component of computer system design, with applications ranging from basic office environments to large-scale, shared database systems. The successful application of those distributed processing concepts to the complex real-time demands of the HST Payload Operations Control Center (POCC) has been a major step in the evolution of spacecraft ground-system architecture.

The implementation of a fully distributed POCC system architecture was achieved with the development of the POCC Refurbishment System (PRS), which became operational in June 1993. The PRS system is the primary real-time ground system for HST operations, providing all capabilities required to monitor and command the HST spacecraft. It is designed to supersede the old HST real-time ground system by supporting both existing and new HST servicing mission requirements in a fully distributed environment. The PRS system provides the basic architecture and design features that will support all HST ground-system needs over the remaining 15-year life of the project. The basic capabilities of the PRS system provide:

- Spacecraft telemetry acquisition from external data networks at rates up to 1 Megabit/second.
- Spacecraft telemetry decommutation and conversion.

- Spacecraft telemetry subset extraction and transmission to the HST Science Institute in Baltimore, MD.
- Spacecraft command generation, uplink, and verification via spacecraft telemetry.
- Spacecraft telemetry and ground-system parameter displays in alphanumeric or graphical format (both virtual screen and hardcopy displays).
- Strip Chart Recorder (SCR) plotted display of spacecraft telemetry.
- Archive of all spacecraft data, ground-system events, and spacecraft commands.
- User interface and associated ground-system control language.
- Local Area Network (LAN) configuration and control.

These capabilities have been distributed across specialized nodes on a common, dedicated LAN to support primary real-time functions of the HST ground system, as shown in the figure. Each LAN node performs a distinct (but related) set of functions; the hardware and software components of each node are tailored to those functions. The PRS system consists of four types of nodes as summarized in the table.

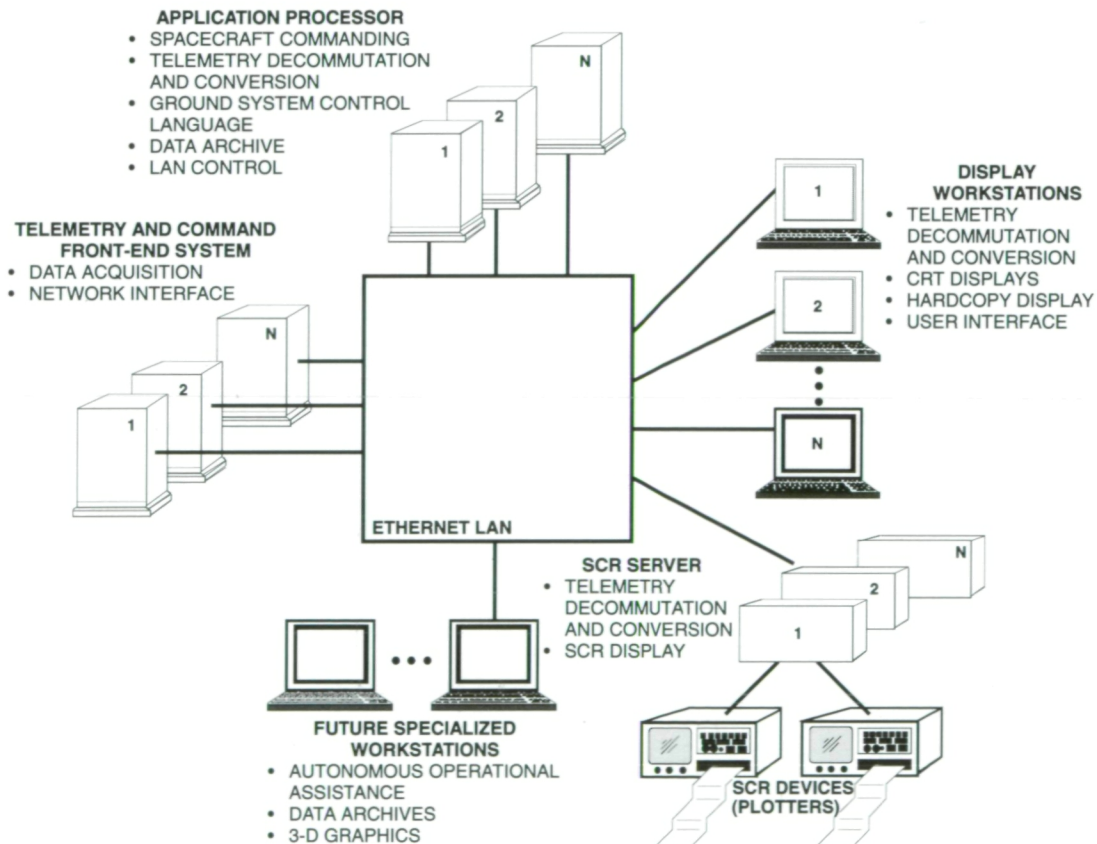
PRS Node Configurations

NODE TYPE	HARDWARE	SOFTWARE
Telemetry and Command (TAC)	DEC PDP 11/84	RSX
Application Processor (AP)	DEC VAX 4000/500	VMS
Display Workstation (workstation)	DEC VAX—station 3100, 3200, or 4000	VMS; OSF MOTIF
SCR Server (SCR)	DEC VAX 4000/400; Astro-Med 95000 SCR devices	VMS

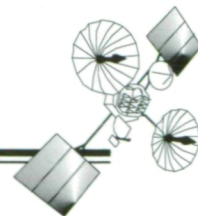
A minimal functional PRS system is known as a string and consists of an AP, a TAC, and at least one workstation. Additional workstations can be added as required, as well as an SCR if hardcopy plots of spacecraft telemetry are desired. The PRS string nodes are integrated into a full, real-time system via the LAN, an Ethernet-based network using DECnet protocol. Spacecraft telemetry is passed to each node in a string and locally decommutated and converted so that it can be used for that particular node's function (i.e., screen display, SCR plot, command verification on the AP, etc.) parallel strings of nodes can be configured on the LAN, allowing spacecraft operations to continue unhindered during servicing mission simulation testing and other ground-system activities. The PRS system is also designed to allow any combination of specific nodes to create strings. For instance, any AP can be connected to any workstation, TAC, or SCR, and any node on one string can be moved into another string within minutes without operational impact to either string. The

distributed PRS architecture is at the heart of this flexibility, allowing rapid response to changing operational needs, equipment failures, or critical peak periods of ground-system activity such as will occur during the servicing mission.

The development of the PRS fully distributed system had many goals, all of which were successfully met. The first of these was to allow easy expandability of the system. With a network of specialized nodes, new nodes can be added to augment processing needs; indeed, this has already occurred as the number of workstations required for the ground system has increased from 21 to more than 40. These increases in capability were easily completed without any significant software changes. Future expansion to over 100 workstation nodes is possible. Hardware and operating systems within the PRS system may be mixed as requirements expand. As outlined in the table, there is already a mix of hardware and operating systems,



PRS Distributed Architecture.



with no impact to system performance. This capability will be emphasized when a planned replacement of the TAC node will introduce a non-DEC hardware platform based on a UNIX-like operating system. This complete changeover on the TAC will only affect a few software modules on the AP node, and have no effect at all on the other nodes. This is of particular importance for a long-term project such as HST, since the capability to use a mix of hardware and software products will provide limitless options for functional system improvement and adaptation to new technologies as they become available.

Distributed processing has also increased system reliability. With distributed architecture, any node that fails can readily be replaced with a duplicate without affecting other system functions on other nodes. Additionally, system hardware or software upgrades can easily be implemented on any node or group of nodes without affecting other nodes. This ensures that any problems resulting from such upgrades are isolated.

Efficient system performance is another achievement of PRS implementation. Due to the use of Ethernet's multicast function, spacecraft telemetry can be transmitted once and received simultaneously by every node on the network. In addition, any number of nodes can be added without increasing network traffic or impacting performance on an existing node. PRS has also distributed functionality so that no node is ever overloaded. The result has been a robust system that is ready to be responsive to future requirements.

The PRS system has been implemented with other HST-related facilities responsible for system development, spacecraft replacement instrument and on-board spacecraft software control systems testing. In these cases, PRS is used in a simulation and test mode, receiving simulated spacecraft telemetry, and sending spacecraft commands to test instruments or simulators. The distributed nature of PRS allows these facilities to pick types and numbers of nodes without inducing any software changes. The use of PRS in these facilities rapidly provided required capability, and prevented large system development expenditures. In addition, these facilities now may connect their PRS workstations to the operational PRS ground system for joint servicing mission activities.

PRS system architecture provides the basis for expanding capabilities as the operational environment of the HST ground system evolves to meet the growing needs of the HST project. Highly specialized nodes can be added to the network and given access to spacecraft telemetry for their processing needs without impacting the existing system. One such possibility is a workstation with a complete historical archive of spacecraft telemetry, spacecraft commands, ground-system events, and other pertinent data that would provide correlated displays of those data. Such a functional capability would allow ground-system users to analyze all aspects of ground-system and spacecraft operations in a comprehensive, graphical format. Similarly, an autonomous operational assistance workstation could use operational scheduling data (in conjunction with the historical archive described above) to determine when events on the ground system or spacecraft should occur. The system would then alert operations personnel to the nature of the action required and the time of its execution.

The PRS distributed architecture allows easy integration of new capabilities into the existing system with significant benefit to HST ground-system objectives.

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SOLAR AND HELIOSPHERIC OBSERVATORY NEAR-REAL-TIME COMMAND PROCESSING

THE SPACECRAFT command controller operating from a Mission Operations Center (MOC) typically has sole responsibility for transmitting all real-time commands to the spacecraft and its instruments. This requires that experimenters plan nominal and contingency command sequences ahead of time, and coordinate their execution with the command controller as needed. For the Solar and Heliospheric Observatory (SOHO) mission, the experimenters require a much more automated system that allows them to interactively command their instruments in response to observations found in the real-time science telemetry. The SOHO MOC (SMOC), being built by the Mission Operations Division (Code 510), will meet this need.

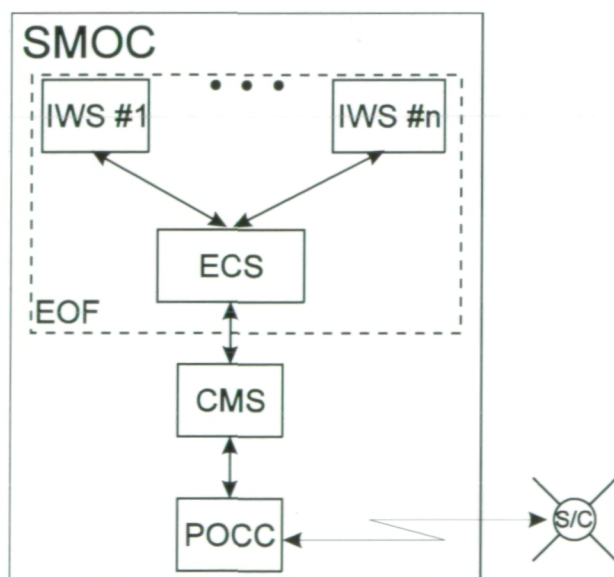
The SMOC is comprised of an Experimenter Operations Facility (EOF), a Command Management System (CMS) and a POCC. These three collocated systems work in concert to provide SOHO experimenters with the ability to routinely uplink real-time instrument commands from their instrument workstations (IWSs). The EOF Core System (ECS) provides the IWSs with a central interface to the CMS and POCC systems. These components support near-real-time (NRT) command, as depicted in the figure. The EOF is the focal point for all science operations and is comprised of the ECS and the experimenter

IWSs. Besides providing a central point of contact with the CMS and POCC systems, the ECS also provides instrument command verification and prioritization. The IWSs are responsible for the software that generates the instrument command sequences. The EOF provides the environment for the experimenters and flight operations team to coordinate science campaigns during real-time operations.

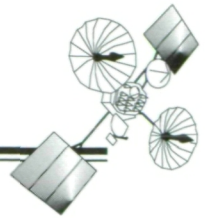
The IWS real-time commands are sent to the ECS in the form of command groups. The command groups may be sent in either a binary or mnemonic format. The binary format does not require further processing by the CMS or POCC systems, except to wrap the bits within the spacecraft command structure. The mnemonic format requires that the CMS translate the group into a binary format using a command database and wrap within the spacecraft command structure.

The ECS forwards command groups to the CMS as they are received from the IWSs, handling any conflicts based on a pre-established experimenter priority scheme. The CMS automatically processes the groups, checking to ensure that the originator identifier and the destination instrument correspond to each other. If appropriate, the CMS checks the command mnemonics to ensure that they are on an approved list for use by the experimenters. If they are not on the approved list, the CMS will reject those command groups and disable the experimenter's contact until a reset message is sent to the CMS. Once the command groups have been validated, the CMS converts the mnemonics to command bit patterns and forwards them to the POCC.

During spacecraft contacts, the SMOC command controller allocates blocks of time in which the experimenters are able to perform NRT command of their instruments. The SOHO project has been allocated one 8-hour and three 1.6-hour passes per day by the Deep Space Network. When the SMOC command controller enables NRT command, referred to as the throughput mode, a path is established between the IWSs and the POCC via the ECS and CMS. The SMOC command controller, in effect, gives temporary command authority to the experimenters to command their instruments. During NRT command, messages are sent to the IWSs to keep them abreast of instrument command activity status.



Components supporting near-real-time command.



The POCC handles the actual uplink of the instrument command groups to the spacecraft. Regardless of the original format, the groups are always presented to the POCC by the CMS in binary format, ready for uplink. One challenge to NRT command support is that, although there may be several IWSs desiring command support simultaneously, there is only one 2-kilobit-per-second (kbps) uplink path to the spacecraft. In addition, due to the orbit, the spacecraft is always at least 5 light-seconds away, so that command uplink and verification takes at least 10 seconds. In an effort to maximize the available uplink resource, the CMS and POCC systems work together to maintain a command group queue that establishes a path from the CMS through the POCC to the spacecraft. The goal is to ensure that use of the 2-kbps uplink channel is maximized to its fullest. An experimenter can also send requests to the POCC via the CMS to have a sequence of commands uplinked that are already resident in the POCC. These are referred to as Predefined Command Sequences (PCSs). Upon receiving and validating the request, referred to as a Remote Command Request (RCR), the POCC uplinks the PCS essentially as if it were a normal command group received from the CMS. The PCSs, in fact, are bound by the same rules as normal command groups (i.e., no spacecraft or critical instrument commands are permitted).

When an experimenter does have the need to uplink real-time spacecraft or critical instrument commands during NRT command support, an electronic message may be sent to the POCC via the CMS to request the SMOC command controller to execute a specified command procedure. The request, referred to as a Remote Procedure Request (RPR), causes the POCC to issue an audible alarm to ensure that the SMOC command controller is aware of the request. The POCC also checks to see if the RPR is on an approved list and notifies the controller appropriately. If approved, the command controller manually executes the requested command procedure.

The SMOC command controller only gets involved during this period if a spacecraft or instrument anomaly is detected or if commands are needed for which the instrument researchers are not authorized. The latter typically occurs if the experimenter requires the uplink of real-time spacecraft or critical instrument commands. These command types cannot be uplinked by the experimenter via the throughput mode. In the event that SMOC command controller action is needed, the controller first pauses or disables the throughput mode, issues the needed commands, and, if appropriate, re-enables the throughput mode to resume NRT command.

To coordinate procedure processing in the POCC, the throughput mode must be placed in a paused state prior to uplinking the requested commands. To reduce SMOC command controller activity and potential for error, a convention exists in which all command procedures that can be requested via the RPR must automatically pause and resume the throughput mode appropriately.

Information pertaining to the status of the command procedure execution is made available to the IWS via directives that must be embedded in the procedure. These directives allow the experimenters to essentially send themselves electronic messages from the POCC to the IWSs. The RPR process effectively removes the need for the experimenter to always rely on voice communications to have POCC-resident command procedures executed when needed. It also provides for better record-keeping and configuration control.

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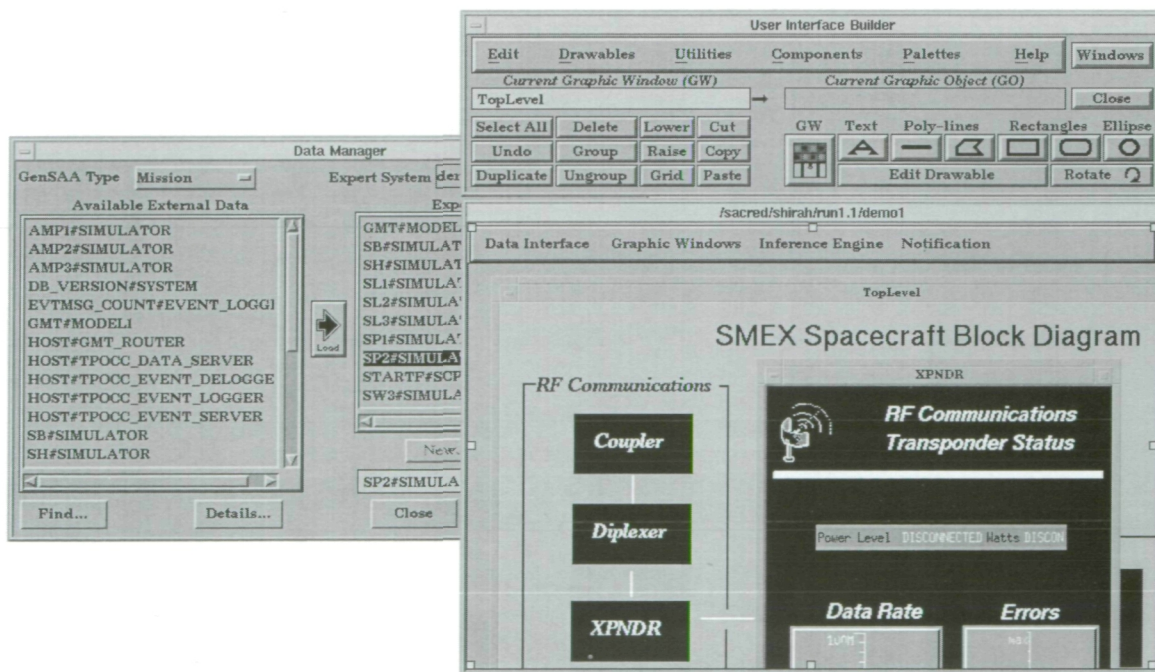
ADVANCING SATELLITE OPERATIONS WITH GRAPHICAL EXPERT SYSTEMS

FOUR TIMES a day, for ~10 minutes, two satellite controllers in the Solar Anomalous and Magnetospheric Particle Experiment (SAMPEX) Control Center at GSFC monitor hundreds of telemetry parameters on 21 textual display pages and 12 graphical stripcharts in order to assess the health and welfare of the spacecraft. The task is routine and mechanical. Most of these real-time spacecraft contacts are problem-free; however, when a problem is detected, the controllers must quickly isolate the cause and determine the proper course of action.

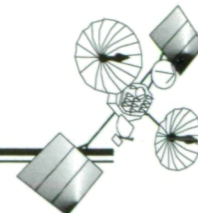
As satellites become more complex and the number of parameters increases (e.g., SAMPEX has over 2,700 parameters), real-time operations are becoming more difficult for satellite controllers to perform manually. The need to automate some data monitoring functions is apparent. In the coming years, GSFC plans to operate an increased number of satellites, but will face declining budgets. Satellite operations and ground-system development clearly must be accomplished at reduced costs.

To address these issues, the Automation Technology Section has developed a new domain-specific expert system development tool called the Generic Spacecraft Analyst Assistant (GenSAA). GenSAA is an advanced software tool that enables spacecraft analysts to rapidly build simple, yet highly graphical expert systems that are capable of performing real-time spacecraft monitoring and fault-isolation functions. Initial development of GenSAA began in 1991; activities in 1993 included full system development and first delivery of a working system, as of September.

GenSAA is composed of an integrated set of utilities, called the GenSAA Workbench, and a runtime executive called the GenSAA Runtime Framework. The expert-system developer uses the Workbench for laying out the graphical user interface, defining fault detection rules, and selecting the telemetry data to drive the system. GenSAA insulates the spacecraft analyst from the complicated programming details of the data source (spacecraft ground



The GenSAA Workbench provides a highly graphical expert-system development environment.



system) and the graphical user interface. The Workbench creates a set of files which are used by the GenSAA Runtime Framework to define the executable GenSAA expert system.

Expert systems developed with GenSAA will be:

- **Easily created and modified**—The process for developing specific expert systems using GenSAA is straightforward enough that it can be performed by trained spacecraft analysts on the flight operations team. No compilation step is necessary before executing the expert system.
- **Rule-based**—GenSAA supports the use of rules to represent spacecraft and payload monitoring and fault isolation knowledge. Rule-based representations are easily learned and can be used to describe many of the reasoning processes used by spacecraft analysts.
- **Highly graphical**—The GenSAA operational user interface is highly graphical and X Windows-based. It supports both textual and graphical presentations of satellite health and status information and fault isolation conclusions. GenSAA user interfaces are built with the GenSAA Workbench, which insulates the user from the complexities of X Windows and the Motif widget set. Hyperlink techniques are supported to simplify navigation between GenSAA windows.
- **Transparently interfaced with the data source**—GenSAA is being used to create expert systems that will support analysts in spacecraft control centers that use the new Transportable Payload Operations Control Center (TPOCC) architecture. TPOCC is a UNIX-based control-center system architecture that will be used for many new spacecraft missions at GSFC. Efforts have begun to investigate the adaptation of GenSAA to support non-TPOCC data interfaces.

- **Real time**—GenSAA expert systems will be driven by real-time spacecraft telemetry that indicates the current status of the spacecraft and its operation.

GenSAA is well-suited for use on spacecraft projects that involve a series of similar but non-identical missions such as NASA's Small Explorer (SMEX) and International Solar Terrestrial Physics (ISTP) programs. It is currently being applied to the SAMPEX, Fast Auroral Snapshot Explorer (FAST), and the Wind/Polar missions in these programs.

GenSAA provides an evolutionary approach to automating satellite operations. Although GenSAA is expected to increase automation and operator effectiveness, it has not been determined whether it will scale up to the larger problem of a fully automated control center. Initial operational experiences with GenSAA will provide valuable insights into how automation can be effectively increased to produce highly autonomous spacecraft operations.

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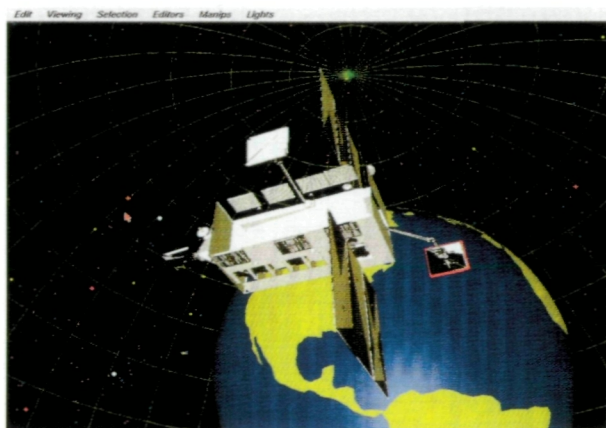
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SPACE VIEWS

SPACE VIEWS is an object-oriented graphical spacecraft monitoring system designed to provide 2-D and 3-D color displays, both in real-time and off-line, that allow flight operations personnel and analysts to better understand the dynamic state of the spacecraft. Space Views shows the spacecraft's position and attitude relative to the Sun, Earth, Moon, stars, TDRSs, and ground stations. Additionally, Space Views displays the spacecraft's predicted orbit path, antenna and instrument fields of view, orientation of steerable antennas and solar arrays, and other items of interest to the user.



Space Views display of XTE spacecraft.

Space Views is being developed using Coad and Yourdon object-oriented analysis and design methodology, C++, X Window, and Motif, and runs on Hewlett-Packard and Silicon Graphics workstations. Space Views incorporates Silicon Graphics *Inventor*, a 3-D graphics tool kit, and will allow interfacing with the Analytical Graphics, Inc. (AGI) *Satellite Tool Kit* (STK). A custom tool developed by Computer Sciences Corporation automatically converts Motif User Interface Language (UIL) files created with the *Builder Xcessory* user interface tool into C++ classes.

The development of Space Views derives from a re-engineering of the Compton Gamma Ray Observatory (CGRO) Graphical Spacecraft Monitoring System (GSMS). Whereas the CGRO GSMS was a pilot project tailored to meet the requirements of CGRO analysts, Space Views is designed to be a generic tool that can be used with all TPOCC-based ground systems. Space Views is being developed based on current and evolving industry standards to facilitate portability among workstation platforms.

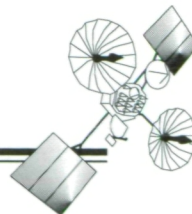
By using several COTS products, increased capabilities are available in Space Views beyond those originally provided in the CGRO GSMS. These include field-of-view translucency, arbitrary view points, user control of object appearance and colors, standard spacecraft database structure, and printing of scenes in PostScript format. Future enhancements include use of OpenGL, an emerging computer-graphics standard that provides a client/server architecture for distributing 3-D graphics displays over a LAN under X Windows.

Space Views is scheduled to be fully operational by October 1994, in the X-Ray Timing Explorer (XTE) MOC at GSFC. This work was done in collaboration with Doug Carlton and David W. Vaules, Jr., of the Computer Sciences Corporation.

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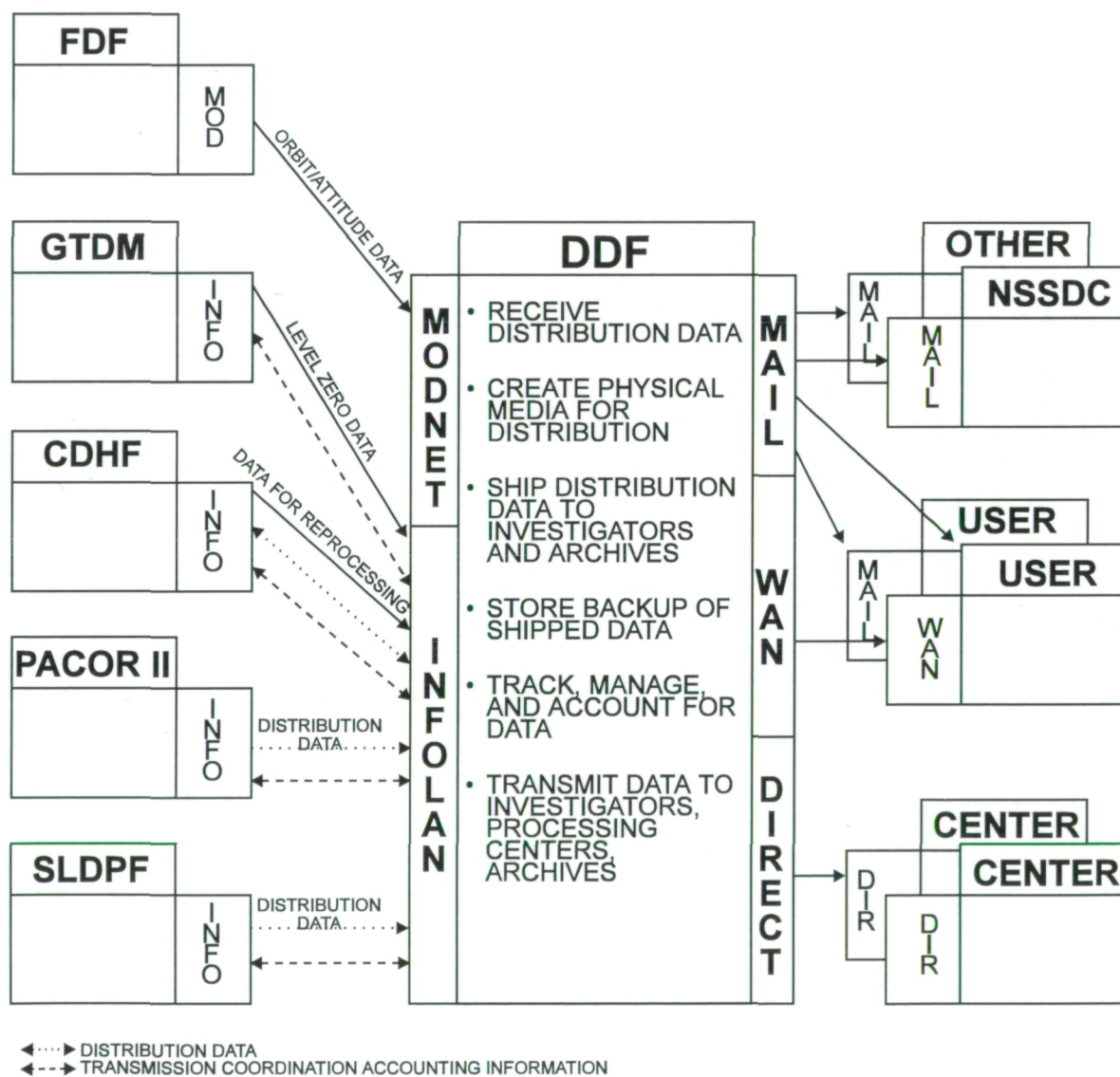


DATA DISTRIBUTION

IPD'S DATA DISTRIBUTION FACILITY

THE DATA DISTRIBUTION FACILITY (DDF) provides data distribution and delivery functions for the GSFC's Information Processing Division (IPD). In this way, the IPD saves the expense of having to build, operate, and maintain unique and distinct facilities and procedures for each mission, while still gaining the ability to better serve its customers. The data are received from

IPD's data capture and processing facilities over MODNET and are distributed to customers either electronically or on physical media. The interfaces and functionality for the full DDF are illustrated in the context diagram shown in the first figure. The DDF can easily be upgraded to new distribution technologies as they mature and become adopted as standards.



DDF Functions and Interfaces.

The DDF is being developed in three phases, each building upon the earlier phases. The first two phases were developed on limited budgets in order to meet immediate requirements, while still establishing the groundwork for future development. Phase I started operations in 1992, supporting magnetic tape distribution for ISTP's Geotail mission. During fiscal year (FY) 1993, the DDF moved into Phase II operations. The focus of Phase II has been the generation of products on CD-ROM in addition to tape distribution. This medium is physically compact and information-dense, allowing for reductions in data handling costs. In addition, the readers for this medium are readily available for all platforms at a cost of less than \$500, thereby greatly reducing data access costs for customers.

The DDF currently distributes several products on CD-ROM. Some of these products will be distributed on a nearly daily basis, while others may be distributed on a quarterly basis, as a function of the capacity of the media (currently 650 Mbytes for CD-ROM) and the turnaround time needed. Some of these products will be distributed to only a few investigators, while others may be distributed to as many as 100 investigators. To distribute these products, the DDF will produce an average of 8 CD-ROMs per day in 1993, increasing to over 50 per day in 1994, and increasing to over 75 per day in 1995. These numbers do not include the copies being duplicated at an external facility, or data being distributed either electronically or on tape.

The CD-ROMs produced by the DDF conform to ISO 9660, which defines both the physical and logical format of the CD-ROM. This assures that most CD-ROM drives on most platforms will be able to read the disk. In addition, the CD-ROMs produced by the DDF follow other emerging NASA standards, guidelines, and practices, especially the use of CCSDS's Standard Formatted Data Units (SFDUs), and a file naming and directory structure which will be compatible with most platforms. For example, all copies of a CD-ROM are uniquely identified by one volume identifier. No other CD-ROM is labelled with the same identifier. Even an update has a different volume identifier from the volume it succeeds. Every CD-ROM also contains several files which help describe the data on the disk. The root directory contains the file VOLDESC.SFD. This is an SFDU-encapsulated file containing an ASCII listing of the files on the CD-ROM. The root directory also contains subdirectories for indices, documentation, and data. The DOCUMENT

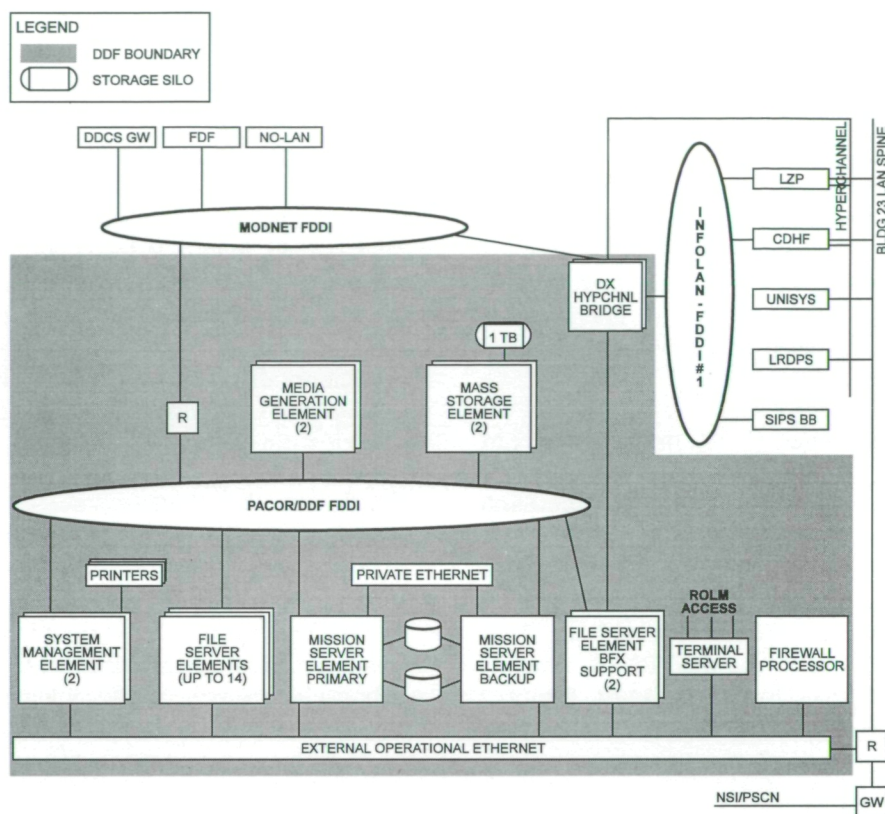
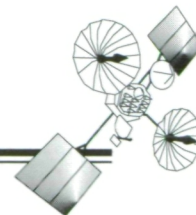
subdirectory contains a file of abstracts which provides a high-level description of the data product. The INDEX subdirectory contains a file which provides a cumulative index for the data product. This file allows the user to determine which CD-ROM contains other files produced for the data product. The data directory contains additional subdirectories which allow the data to be grouped logically, dependent upon the product. This phase will also support ISTP's Wind and Polar missions (to be launched in 1994), as well as a few Spacelab missions including SLS-2.

This earlier work serves as a prototype for Phase III, which will incorporate the latest technologies and standards. Phase III DDF will provide an integrated and flexible system for supporting multiple missions with a range of physical and electronic distribution capabilities, while also greatly reducing the amount of manual operations required. Additional missions to be supported during this phase include the XTE, Tropical Rainfall Measuring Mission (TRMM), ISTP's SOHO, and SMEX. During Phase III, the DDF is being implemented as a distributed, open-architecture system based on a network of low-cost workstation-class systems. As shown in the second figure, the DDF will consist of the following:

- A Mission Service Element (MSE) performing database management and applications processing;
- Several File Server Elements (FSEs) comprising a shared file system;
- Media Generation Elements (MGEs) to create media for distribution;
- Mass Store Elements for retention of data products;
- A System Management Element (SME) providing consolidated status display and control;
- A Firewall Element to restrict access of users of public networks to other DDF elements;
- A Communications Element to interconnect the DDF elements and to provide the interface with external systems.

In FY93 we achieved these major objectives:

- Began operational production of CD-ROMs distributing data to Spacelab and ISTP customers;



DDF Phase III Architecture.

- Designed the architecture for Phase III documenting results and presenting at an IPD Preliminary Design Review;
- Developed the detailed design for Phase III and presented results at an IPD Critical Design Review;
- Acquired initial hardware for Phase III.

We expect that the centralization of the distribution function within the IPD will provide cost savings, in terms of both operations and development. Additional benefits will also be derived from the promotion of the use of standard output products, the enhancement of operations utilizing expert-system technology, and the automation of operator functions in the quality analysis and accounting area.

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Sponsor: Office of Space Communications

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Patricia Carreon serves as DDF's Communications Manager. She received a BS in Electrical Engineering at Southern Methodist University, and is finishing requirements for an MS at George Mason University. She joined IPD in 1989.

Jeannine Shirley is responsible for software development for the DDF. She received a BS in Mathematics from Bowie State University. Since she came to GSFC as a cooperative student in 1984, she has been developing systems for operations support of various missions used for data collection and transmission.

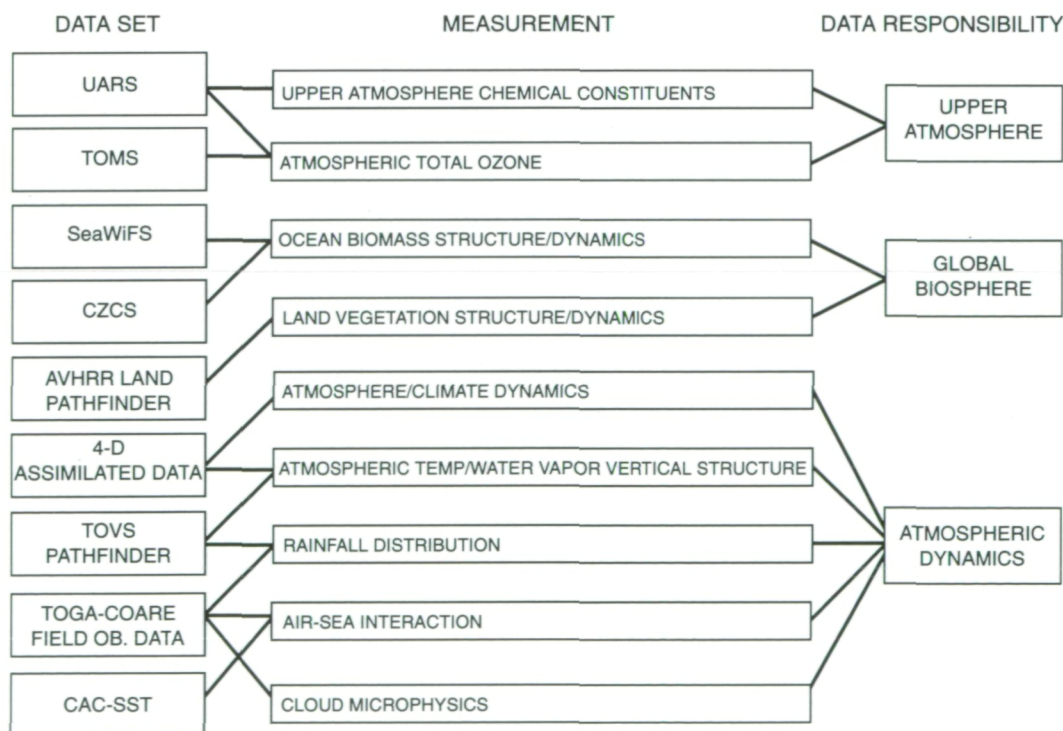
THE GODDARD DISTRIBUTED ACTIVE ARCHIVE CENTER VERSION-0 SYSTEM

THE GODDARD Distributed Active Archive Center (GDAAC) is part of NASA's Earth Science Data and Information System (ESDIS). ESDIS is being developed with a distributed, open-system architecture. Data held within ESDIS are distributed across the U.S. in eight DAACs, each associated with an existing research institution. The ESDIS, as a whole, will be interoperable among the eight DAACs, such that the distinction is transparent to the users.

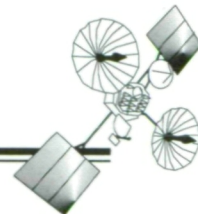
The Earth Observing System (EOS), the main source of data for the GDAAC, is a series of polar-orbiting satellites that will make extended observation of the Earth and its environment. NASA will launch the first EOS satellite in 1998. In addition, the GDAAC will archive data from other sources such as the Upper Atmosphere Research Satellite (UARS), the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), and the TRMM, which is scheduled for a 1997 launch. Other GDAAC data will include meteorological observations, and data from field campaigns.

The GDAAC is responsible for processing, archiving and distributing datasets related to the upper atmosphere, atmospheric dynamics, and the global biosphere. The first figure maps the GDAAC data responsibilities to physical parameters and, in turn, to the major archived datasets. The overall direction of the GDAAC is guided by the Project Scientist and the User Working Group (UWG). The UWG is made up of ~24 eminent scientists in the Earth science disciplines described above. The UWG meets biannually to address specific issues and to provide general direction for the development and operation of the GDAAC.

The GDAAC development is evolutionary. The Version-0 GDAAC is building on the scientific expertise and the heritage of GSFC's NASA Climate Data System and the Pilot Land Data System. The current focus is on ensuring that existing and emerging datasets are preserved and made readily available to the scientific community. The GDAAC is already operational, and is providing incremental user services as development proceeds towards culmination



The GDAAC data responsibilities are mapped to the physical measurements and archived datasets.



in an operational Version-0 system in July 1994. Hughes Applied Information Systems is developing the full-capacity Version-1 system based on the experience and lessons learned from the operation of the Version-0 system. The Version-1 system, to be delivered in a number of incremental releases, is scheduled for an initial release by 1997, to be ready for the 1998 launch of the first spacecraft of the EOS era, the EOS AM-1.

As with all DAACs, the GDAAC consists of three elements. The Product Generation System (PGS) receives raw data and processes them into scientific data products based on algorithm software provided by scientists. The current Data Archive and Distribution System (DADS) consists of 10 terabytes of mass storage in two robotic jukeboxes, and a distribution capability that uses magnetic-tape media and electronic file transfer. The Information Management System (IMS) allows the user to access the GDAAC from a remote terminal to perform metadata searches, seek on-line help, browse through data files, and request data products.

The table summarizes the GDAAC's FY93 accomplishments in implementing datasets. In addition, major planning activities for new datasets took place in FY93. As a

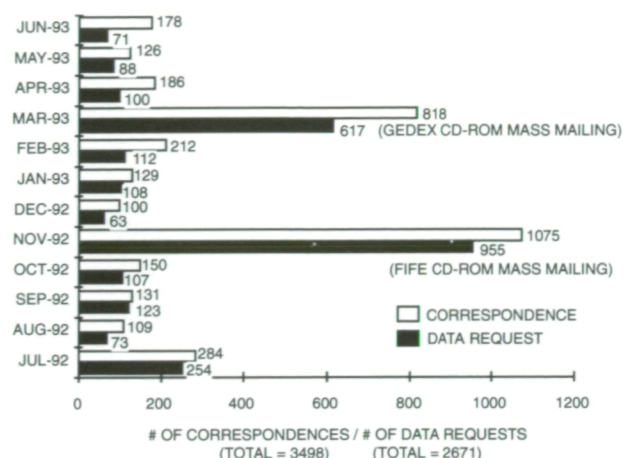
result of these planning activities, the GDAAC began distributing UARS AVHRR and Coastal Zone Color Scanner (CZCS) data to the science community in October 1993, and will begin archiving and distributing TOGA-COARE field observation data and 4-D assimilated data in FY94. The distribution of SeaWiFS ocean-color data to authorized users will begin shortly after satellite launch in mid-1994.

Other FY93 GDAAC accomplishments include the completion of several preliminary releases of the Version-0 IMS and DADS software, and the installation of 10 terabytes of mass storage and other hardware infrastructure.

Users can inquire about the GDAAC's data archive through the on-line IMS or through the User Support Office (USO), which provides personalized help to users. The second figure shows the user statistics for the 12 months ending in June 1993. During this period, the GDAAC received 3,500 inquiries about its existing archived data, and distributed over 2,600 datasets using magnetic tapes, CD-ROMs, or electronic file transfer. As a result of the addition of new equipment, by the third quarter of 1994, the GDAAC will be able to distribute 60 gigabytes of data per day.

FY93 GDAAC accomplishments in dataset implementation

DATA SET	FY93 ACCOMPLISHMENTS/STATUS
SeaWiFS	Ready for GDAAC end-to-end (ingest, archive and distribution) testing by December 1993.
AVHRR Land Pathfinder	• Currently provides archive and distribution support. • Plans to begin processing the data by October 1994.
UARS	• Provides archive and distribution support for level 3A data. • Plans to support the other data levels in FY94.
TOVS Pathfinder	• Provides archive and distribution support for Level 3 benchmark data. • Plans to support all other data levels in FY94.
CZCS	Provides archive and distribution support.
4D Assimilated Data	Provides archive and distribution support for a subset of the five year data set.
TOGA-COARE	Ready to ingest data and provide archive and distribution support in FY94.



User activity between July 1992 and June 1993.

The Version-1 data volume requirements are more than an order of magnitude larger than the Version-0 system. However, data volume is not the only challenge; the GDAAC will implement some of the most complex scientific software extant in retrieving physical parameters from raw data (e.g., the retrieval of vertical atmospheric temperature and water-vapor profiles) and assimilating data from satellite and *in situ* observations using general

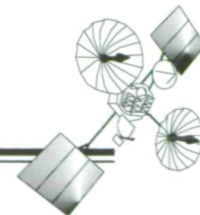
circulation models. The complexity is further compounded by a host of operational activities including provision of user support services, reprocessing of data, and ingesting *in situ* ground-truth data to support satellite data processing.

In the near-term, the GDAAC Version-0 system will continue to archive and distribute existing and new datasets. In the meantime, the GDAAC must devote part of its energy to long-term ESDIS concerns and activities, such as: communicating the Version-0 lessons-learned to the Version-1 developers, preparing the GDAAC to transition from Version-0 to Version-1, and participating in the development of Version-1 by communicating the science requirements to the Version-1 developers.

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Sponsor: Office of Mission to Planet Earth

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TROPICAL RAINFALL MEASURING MISSION SCIENCE DATA AND INFORMATION SYSTEM PROTOTYPE

TRMM IS A SCIENTIFIC investigation of tropical rainfall and its impact on the global energy and water cycles and on the global circulation. The launch of the observatory that will contain the TRMM spaceborne instruments is planned for August 1997.

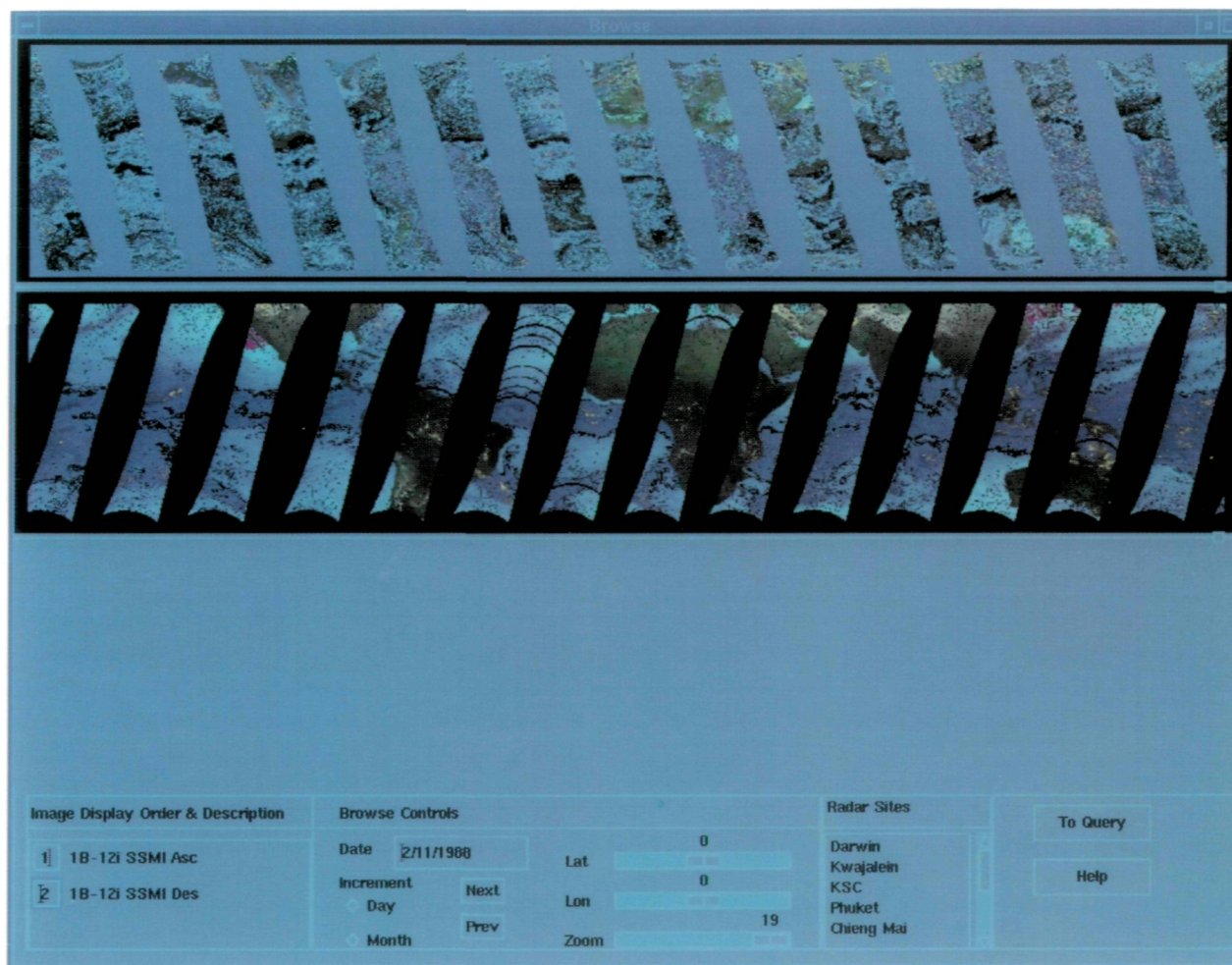
TRMM Science Data and Information System (TSDIS), which is part of the TRMM ground system, has the responsibility for producing standard science products from the TRMM science data. The TSDIS will process data from three of the five scientific instruments to be flown on the TRMM satellite. They are the TRMM Microwave Imager (TMI), the Precipitation Radar (PR), and the Visible Infrared Scanner (VIRS). In addition to these spaceborne instruments, the TSDIS will also process ground-based radar data received from about 10 TRMM data-validation radar stations. The TSDIS will produce more than 50 standard science products. These products will be distributed to the TRMM Science Team members responsible for the science algorithm development and instrument characterization and archived at the EOSDIS. The total daily data volume the TSDIS will process is estimated at more than 60 gigabytes (GB). The algorithms for the standard product generation will be coded by the TRMM Science Team and integrated into the operational TSDIS. As a first step toward the development of the operational TSDIS, a prototype system is being developed to identify developmental risk areas, and to find and demonstrate solutions to reduce these risks.

The TSDIS prototype is being developed in two phases. One of the key objectives of Phase I, completed early in 1993, was to prototype a capability that allows science users to search for scientific data of interest quickly and with minimal effort. This capability is crucial to the operational TSDIS because of the very large amounts of data handled daily. The major objectives of the Phase II Prototype, which is currently under development, are to prototype a methodology for testing and integrating into the operational TSDIS the science algorithms developed by science team members who possess varying degrees of software development experience, and to prototype the important functions of an automated production system that provides planning and scheduling for data-processing operations for a system whose production flow and data dependency are highly complex. The latter objective is further complicated by reprocessing and special processing requirements.

The Phase I system runs on an SGI VGX/340 workstation. A few simple science algorithms were implemented so that the system functionality could be evaluated. These algorithms were supplemented with 3 days worth of science data from Special Sensor Microwave Imager (SSM/I), Advanced Very High Resolution Radiometer (AVHRR), and ground-based radar, which permitted them to produce Level-1B and Level-2A science products. The associated metadata and browse images were also produced. The browse images are generated in the Hierarchical Data Format (HDF) standard data format. Sample browse images for the precipitation radar reflectivity data were generated using synthetic spaceborne radar data. The database and its associated functions for the Phase I Prototype which support the user interface for data search were built utilizing object-oriented database management system (DBMS) software in the Intelligent Information Fusion System (IIFS), developed by the Information Science and Technology Office (Code 930.1). Graphical user interface (GUI) screens were developed, based on X Window/Motif, which contain functions to query the metadata using arguments such as algorithm ID, time, geographic location, and coincidence of satellite swath with ground radar measurements. Information on the satellite swaths that overlap temporally and spatially with one or more of the ground radar measurements are generated during the data processing and stored in the database. The GUI screens also permit the user to display up to three browse images at once, facilitating identification of correlated features in the data from different instruments or algorithms. A sample browse image display screen (see the figure) shows two browse images of SSM/I data along with image display control functions such as panning, zooming, and image data selection. Each image contains a full 24-hour dataset of either ascending or descending orbits, thus avoiding image data overlap.

Remote-access testing with the Phase I prototype revealed that the communication overhead involving the graphics display using the X-protocol can significantly degrade the performance to an unacceptable level. Restructuring of the user interface program into a client/server architecture is underway as a remedy to this problem.

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TSDIS Prototype browse image display screen.

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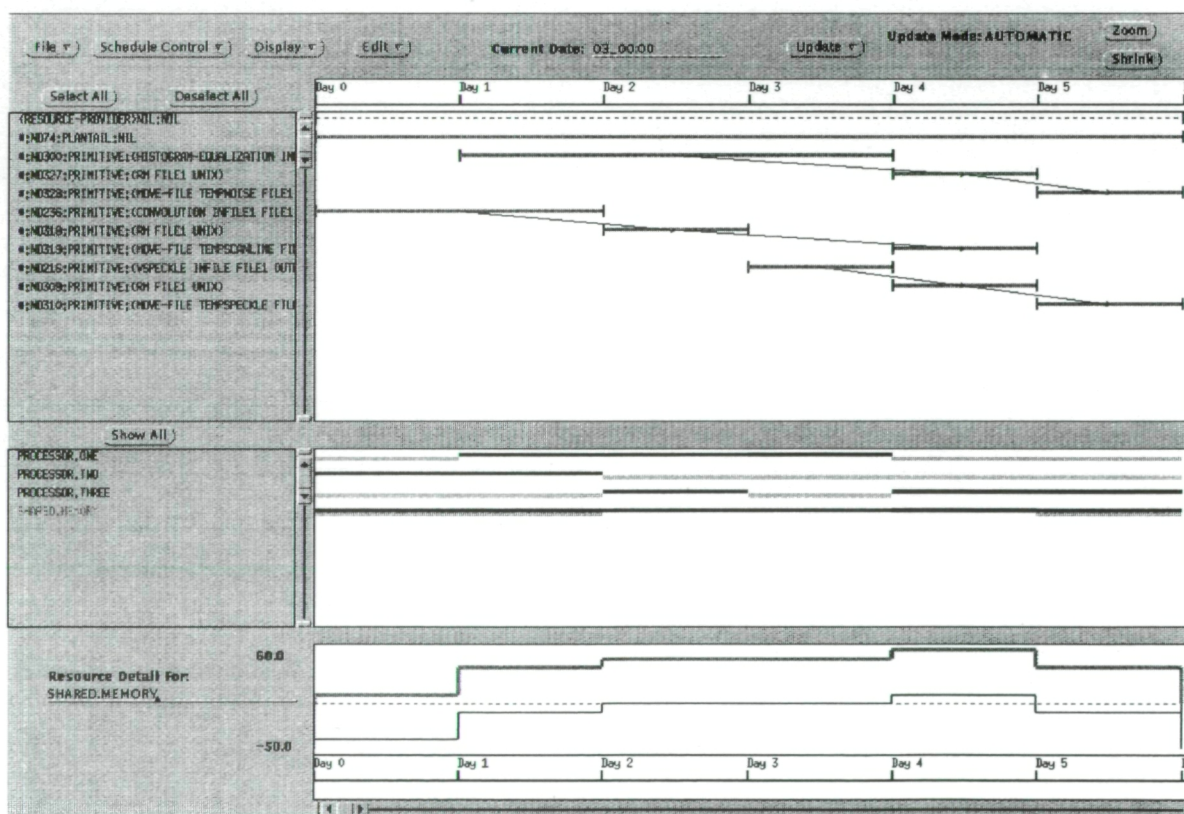
Sponsor: Office of Mission to Planet Earth

Dr. Gi-Kong Kim is the Deputy Project Manager for the TSDIS development project. He earned a PhD in Theoretical Nuclear Physics from the University of Maryland. He has been at GSFC for 3 years, where he works in the Global Change Data Center developing the TSDIS Prototype.

Dr. Michael McCumber is the Science Data Manager for TSDIS. He earned a PhD in Environmental Science (Meteorology) from the University of Virginia. He has worked for most of the last 12 years in numerical modeling in meteorology. For the last year, he has been the science liaison between TSDIS and the TRMM Science Team.

THE SUCCESS of future Earth-science missions depends upon increasing the availability of data to the scientific community responsible for interpreting space-based observations about ozone depletion and greenhouse effects, land vegetation and ocean productivity, and desert/vegetation patterns, among other Earth-system phenomena and processes. GSFC's role, as stated in its Strategic Plan, "...will [be to] take a proactive leadership role in the management of space and Earth science data...in making those data accessible to scientists worldwide...[in order to] foster discipline-oriented and interdisciplinary research using these data."

require that over 1 terabyte of data each day be collected and processed into several levels of science data products. Furthermore, to prevent a backlog of data, processing throughput must match varying collection rates, and all data products must be generated and stored within several hours of observation. Over the minimum 15-year lifetime of EOS, this system will result in an estimated 11,000 terabytes of collected, processed, and stored data. These data will be found by searching through a metadatabase or card catalogue containing simple search keys obtained from instrument engineering specifications, and complex keys derived from the contents or features in the incoming sensor data (e.g., land use/land cover features). Simple keys consist of location, time of observation, etc., and will be easily derived from normal mission operations data holdings. Complex keys must be derived by implementation of various image-processing routines and depicted in



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such forms as maps, lower resolution images, or simple text descriptions.

To ensure that these keys are generated in a reasonable time, a prototype system has been developed that demonstrates features that can be extracted for data rates less than 5 Mb/second. Initially, raw telemetry data are processed to Level 0 by a hardware system called MacTac, developed by GSFC's Microelectronics Systems Branch/Code 521. From Level 0, an intelligent planner/scheduler system, as depicted in the figure, controls the execution of sensor-specific, ground-based algorithms which de-packetize and calibrate the data derived from flight dynamics ephemeris information, preprocessing algorithms which remove noise, and classification algorithms (based on e.g., neural networks) which label the regions in the imagery according to recognizable features. Processing these data is accomplished by the planner/scheduler in a distributed fashion across several workstations and a massively parallel supercomputer. To accelerate data processing, the planner/scheduler chooses the processor(s) to which data processing tasks should be allocated by monitoring network traffic, processor loads, and available disk space. Upon completion of processing, the feature-containing data products are joined with the associated engineering/ephemeris information and stored in a metadatabase. In the approach we use, the complete processed scene is not stored. If requested by a user, the scene and/or standard products for the scene can be generated from the raw data and metadata in the form of thumbnail sketches, composite images, image features, etc. This approach results in vastly reduced storage requirements for a minimal cost in reprocessing time, while allowing sys-

tem managers to modify the priority of standard product generation, and maintaining reasonable turnaround times to accommodate data obtained for catastrophic or anomalous events or other targets of opportunity.

Contributors to this work include Bob Crompt (930.1), Jim Chesney (521), Mark Boddy (Honeywell SRC), Jim White (Honeywell SRC), Becky Short (Code 553.2), Leonard Dickens (U.Md.), Phil Romig (U.Nebraska-Lincoln), and Rob Lovell (Hughes/STX).

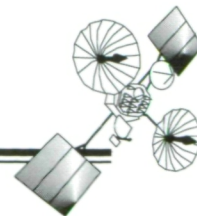
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Sponsor: GSFC Director's Discretionary Fund

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Mr. Toby Bennett is an Electrical Engineer in the Microelectronics Systems Branch. Mr. Bennett earned his BSEE from the University of Maryland. He has been at GSFC for 2 years and is the Acting Section Head for 521.1. Mr. Bennett is responsible for developing VLSI Components and Systems for next-generation data systems.



ROSAT DATA PROCESSING AND ARCHIVING

THE ROENTGEN SATELLITE (ROSAT) U.S. Science Data Center (USRSDC), the National Space Science Data Center (NSSDC), and the High Energy Astrophysics Science Archive Research Center (HEASARC) have teamed to provide rapid access to ROSAT data for Guest Observers (GOs) and public archive researchers. The system both safeguards the proprietary data rights of the GOs and ensures that data are easily available to others once the proprietary period expires. Data are usually available within hours of request via electronic networks and with expenditure of personnel resources. This rapid access to mission data has never before been accomplished to this degree.

In the past, data processing, archive and distribution were labor-intensive efforts. The principal investigator (PI) teams expended years to process telemetry data into scientific products. Often, the NSSDC would not receive archival data until many years after the demise of the mission. The data transfer and distribution media were usually magnetic tapes. When data were requested, an operator needed to select and duplicate the requested file from an archival tape to a distribution tape, then send the data via mail to the requester. Overall, the request-to-receipt process could take 6 to 8 weeks.

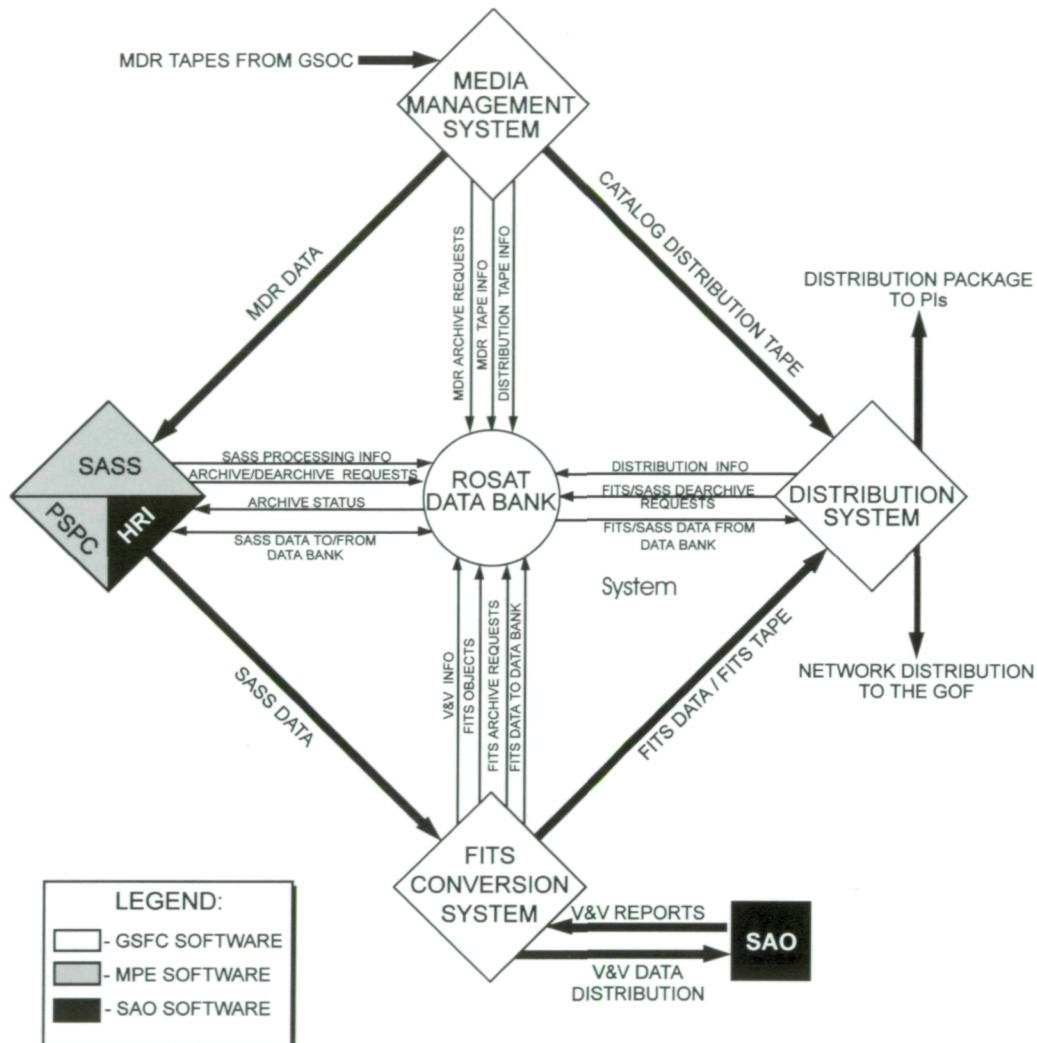
With ROSAT, the GOs normally receive their proprietary data 1 month after observation, which includes delays for U.S. receipt of all inputs necessary for processing from the Max Planck Institute (MPE) in Germany (3 weeks) and time required for processing (1 week). All ROSAT observations are proprietary to the proposing GO for a period of 54 weeks from the date of distribution to the GO. U.S. observations enter the public archive in the NSSDC 58 weeks after observation if no problems are encountered. Both the processing system and the archival system are highly automated compared to previous high-energy astrophysics mission data systems; Write-Once-Read-Many (WORM) optical disk jukeboxes are the main storage media, and relational database management systems support data distribution.

The USRSDC Data Processing and Distribution System provides the user community with calibrated ROSAT data and data products that are used directly for analysis of the observed celestial objects. This overall system (see the first figure) is distributed between GSFC and the

Smithsonian Astrophysical Observatory (SAO). The subsystems are described in the sequence of data flow:

- The Media Management System reads and verifies the incoming raw data tapes received from Germany and copies these data to an optical disk jukebox.
- The Standard Analysis Software System (SASS) controls data flow internally, relying on the INGRES database management system. It applies instrumental aspect corrections and energy calibrations to the data, and then implements suitable algorithms to produce standard data products.
- The Flexible Image Transportation System (FITS) Conversion System gathers information from SASS and generates data files in the FITS format, and creates the data tape to be sent to the GO. The system also extracts relevant trend data and sends it to the Guest Observer Facility (GOF) at GSFC for use by all observers. Data are also forwarded to SAO for validation and verification (V&V).
- The V&V effort and the Quality Assurance System is crucial in guaranteeing that data distributed to GOs are error-free and useful from a scientific standpoint. SAO produces a V&V report that is incorporated into the GO package which contains comments and recommendations to aid the GO in their data analysis.
- The Distribution System tracks and assembles the GO data packages, which consist of the tape, hardcopy, and reference material. Distribution information is tracked by the INGRES database, and used in conjunction with MPE to establish public release dates. The system also sends data electronically to the GOF for visiting GOs and to the public archive.

Except for the V&V effort, the system was designed to be as automated as possible. However, due to errors in the mission timeline as sent by MPE, manual corrections have been necessary to ensure proper SASS operation. This occurs in about 30 percent of the observation sequences, and has impacted processing throughput. The processing team has overcome these difficulties, and data processing and distribution is now almost a routine operation, barring any problems with SASS or the satellite.

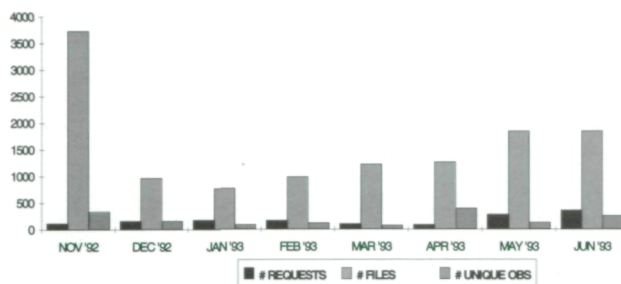
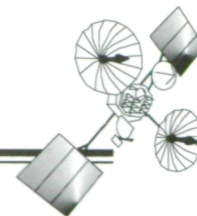


ROSAT Data Processing and Distribution System.

Approximately 180 GB of data are produced by this system per year, of which about 29 GB are FITS data products. This high volume of data must be managed properly to allow quick access by the GOs, the GOF staff, the processing staff, and the public archive, and to make provisions for future data reprocessing. Reprocessing is necessary to correct known software bugs in the processing system; to conform to new data format standards; and to include better understanding of instrument in-orbit performance. The ROSAT Data Bank (RDB) was created to manage the flow of data to and from the optical disk jukebox that serves as the main data storage for proprietary ROSAT data. The RDB allows the processing personnel to automatically manage the raw data, the FITS data, and all the intermediate files that are produced by the SASS.

It interfaces directly with the INGRES database in SASS to keep the disk space available for processing. The RDB is a large hardware/software system developed by the USRSDC at GSFC, as data management software was not available from MPE.

The U.S. ROSAT Public Archive was officially opened on November 1, 1992. The ROSAT public data are physically stored in the NSSDC Data Archive and Distribution Service (NDADS) WORM optical disk jukebox. The USRSDC releases datasets to the public archive monthly. Since data are sent once a month, most of the datasets are still proprietary when transferred to the NDADS system. The datasets will enter the public domain at different dates throughout the month immediately following the data re-



ROSAT Archive Statistics.

lease to NDADS. Once the data are delivered to NDADS, NSSDC is responsible for securing those datasets which are still proprietary. The current ROSAT data volume is about 20 GB, and growing by approximately 0.5 GB per day.

The NDADS is an automated near-line archive system available around the clock. It has a data storage capacity of almost one terabyte. Scientists can access the data using the Automated Retrieval Mail System (ARMS) simply by sending an electronic mail request. Data are staged by NDADS usually within minutes for network retrieval via anonymous file transfer protocol (ftp) or by NSI-DECnet copy. The system also can send the data directly to the requester's computer. ROSAT data retrievals via ARMS have accounted for about 20 percent of all NDADS data requests, with an average of 160 requests per month and 10 files per request. The second figure shows the ROSAT Archive Request Statistics for the first 8 months since the archive opening. The NSSDC also distributes data on magnetic media to scientists that do not have network access. Scientists from the international scientific community including Germany, UK, Turkey, and Japan, have accessed data electronically from the NDADS.

Users who desire a higher level scientific interface can also access the ROSAT public archive using the HEASARC Online Service (BROWSE) or the ROSAT Mission Information and Planning System (MIPS). Both BROWSE and MIPS overlay the ARMS interface with the capability to correlate astronomical names, pointing coordinates, and times of observation with the ROSAT

sequence numbers, which identify the files in the NDADS archive. These systems can also generate a message automatically to ARMS to retrieve the data from NDADS for the user.

Data interchange between the public archives in the U.S., Germany, and the U.K. ensures that all ROSAT public archives have the same observations in them. Data for U.S. and German/U.K. observations are currently in different formats that are specific to their analysis software. In the future, all ROSAT data will be reprocessed to the new rationalized FITS (RFITS) format, providing a single standard data format for all observations. HEASARC has spearheaded an effort to use RFITS as the generalized high-energy astrophysics data format. If the format is adopted by other missions, it will greatly facilitate multimission data analysis.

This report was done in collaboration with Mr. Peter E. Damon, who is a Section Manager for Hughes STX Corporation and is responsible for managing contractor support for the ROSAT, ASCA, and XTE missions' data processing, archiving, and distribution activities.

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Sponsor: Office of Space Science

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ADVANCED SOFTWARE AND SYSTEMS ENGINEERING

REUSE IN THE LARGE: UTILIZING THE EVOLUTIONARY DOMAIN LIFE CYCLE MODEL WITH A KNOWLEDGE-BASED APPROACH

REUSABILITY IS A GOAL in software development that seeks to analyze, design, and develop software which will have certain components available for reuse as-is or with only minor extensions. Software components may be quite similar for different projects. To build the same component more than once is a waste of valuable resources; developing a means for making these potential reusable artifacts available for consideration will mitigate some of this waste. Of course, reuse of components must be planned. From this perspective, reuse in domain-specific environments is an area of great potential. In industry, domain-specific software currently is developed from start to finish without any regard for the development of similar existing systems.

Thus, in the quest for reuse in software engineering, the domain-modeling approach to software development has received much attention. The primary objective of this approach is to increase reuse of code and domain requirements, specifications, and designs. Domain modeling addresses the problem of developing a family of systems in which the traditional system development activities (e.g., analysis specifications and design) are performed at the application domain-level instead of the individual system level. From the domain model, target systems can be generated by tailoring the domain model, or by evolving the domain model and then tailoring it.

The Evolutionary Domain Life Cycle (EDLC) model is a software life-cycle model that seeks to functionally eliminate the distinction between software development and software maintenance. Hence, the model seeks to promote reuse-oriented software development. Using the EDLC paradigm, systems evolve through several iterations. As a result, systems developed using this approach must be capable of adapting to changes in the requirements during each iteration. Because new software systems are often new versions of existing ones, the EDLC model takes an application-domain perspective, allowing the development of families of systems.

When considering the development of a family of systems, it is necessary to replace the traditional system development activities of requirements analysis, specification, and system design with activities that span the entire application domain: domain analysis, specification, and domain design. Domain analysis involves the analysis of existing target systems in the application do-

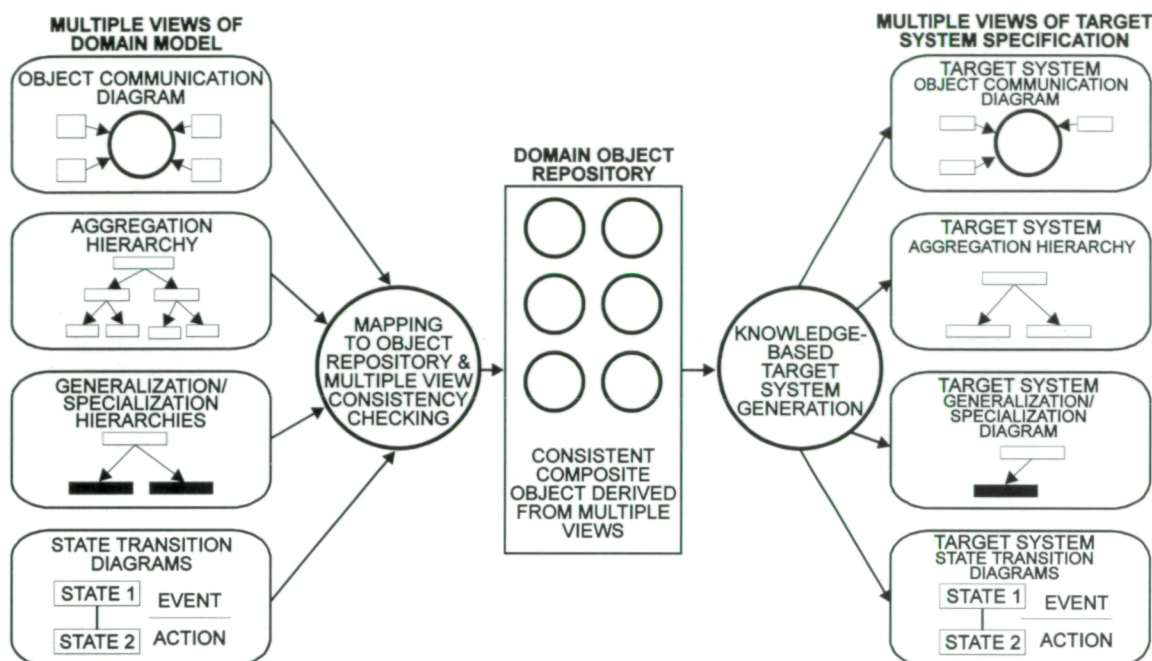
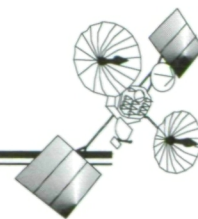
main, and interviewing domain experts to capture their knowledge of existing features, including known or anticipated variations in the domain.

During domain modeling, reusable specifications and architectures are developed that capture the similarities and variations of the family of systems that compose the application domain. The specifications are the result of domain analysis in which current and anticipated future requirements are addressed for the family of systems. Since all future changes will likely not be anticipated, the domain specification must be capable of evolving as new requirements are added and existing ones are changed in unanticipated ways.

It should be noted that the domain modeling method is object-oriented, since the object-oriented paradigm is deemed highly conducive to system evolution, and promotes ease of maintenance. This is because objects support the concepts of information hiding, abstraction, and inheritance. In addition, objects can be modeled as concurrent processes which communicate via message passing, and objects have a number of finite, valid states which can be modeled with finite-state machines.

A domain model is a multiple-view representation of the application domain that captures the similarities and variations of the family of systems that compose the domain, as shown in the figure. Each view presents a different aspect of the domain. The different views, as specified below, are developed iteratively.

- **Aggregation Hierarchy.** The Aggregation Hierarchy is used to decompose complex, aggregate object types into less-complex object types, eventually leading to simple object types at the leaf nodes of the hierarchy. Object types are either required in every target system or optional for some target systems.
- **Object Communication Diagrams.** Objects in the real world are modeled as concurrent processes that communicate with each other using messages. The object communication diagrams, which are hierarchically structured, show how objects communicate with each other.
- **Generalization/Specialization Hierarchies.** As the requirements of a given object type are changed to meet the needs of a given target system, the object



Development of Domain Model to Generation of Target System Specification.

type may be specialized by adding, modifying, or suppressing operations. The variants of a domain object type are stored in this hierarchy.

- **State Transition Diagrams.** Because each active object is modeled as a sequential process, it may be defined by means of a finite-state machine and documented using a state transition diagram.

Once the domain model has been developed, the information in the multiple views is extracted, checked for consistency, and stored in an object repository. The object repository interfaces with knowledge-based tools and provides the informal and formal specifications for reuse. Thus, the object repository provides a unique and consistent specification of the domain model, and this can be accessed by various tools.

Once the domain modeling activity is completed, the domain specification serves as the framework for generating target systems. As stated previously, a target system specification is derived from the domain model by tailoring it according to the requirements specified for the target system. The process consists of the following steps: (a) accessing and retrieving necessary components from the various knowledge sources; (b) displaying the infor-

mation to the target system engineer; (c) eliciting the target system requirements from the target system engineer; (d) reasoning about the interfeature and feature/object dependencies to ensure consistency; (e) tailoring the domain specification to generate the target system; and (f) conducting target system consistency checking.

Once the consistency checking is finished, the domain model graphical views are tailored to generate the same set of graphical views for the target system. These two sets of graphical views differ in that only those objects required for the entire domain *and those specified for a particular target system* are used to create the views.

In efforts to explore and demonstrate the EDLC and domain modeling concepts mentioned above, a proof-of-concept experiment that entails the development of a prototype, Knowledge Based Software Engineering Environment (KBSEE) has been conducted by the Center for Software Systems Engineering at George Mason University. This tool uses both COTS software and custom-developed software to provide support for a domain-independent environment which may be used to support the development of a domain model for any application that has been analyzed. There is also support for generating target system specifications, given system re-

quirements. In relation to GSFC, KBSEE has been used to demonstrate a version of the POCC domain model. The work has been ongoing for about 2.5 years. The system was made operational in 1993 and installed in the Data Systems Technology Laboratory at GSFC. It is currently undergoing enhancements and operational testing; plans are in place to use KBSEE for advanced work in the Mission Operations Division in the modeling area.

Future work entails extending the current domain modeling capabilities to a distributed programming environment, and to implement the EDLC paradigm to support target system construction, instantiation, and code reuse. The work done so far seems promising, as the area of domain modeling and design is vital to the development of reuse-oriented software.

Primary contributors to the ideas and work presented here include Hassan Goma, Larry Kerschberg, Vijayan Sugumaran, and Iraj Tavakoli of the Center for Software Systems Engineering at George Mason University. This

work was done in collaboration with Dianne Isom of the University of Minnesota.

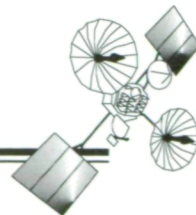
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REUSABLE SOFTWARE COMPONENTS FOR MONITORING AND CONTROL OF TELEMETRY PROCESSING SYSTEMS

OVER THE LAST 10 YEARS, the Data Systems Technology Division of GSFC has developed a generalized set of functional telemetry processing components. These components utilize hardware based on Very Large Scale Integration (VLSI) and application-specific integrated circuits (ASICs). These components have been used, in various combinations, in numerous mission ground systems. They also provide a framework for the assembly of telemetry-data ground systems for future space projects such as the EOS and SMEX mission series. Implementation of the ground systems for such projects is based on a common set of functional components, and provides cost benefits in system development and maintenance.

To extend this paradigm and gain further cost benefits, we have utilized a similar approach and created a set of reusable software components for the implementation of telemetry ground-system monitoring and control functions. Using suitable combinations of modifiable hardware and software components allows for rapid, cost-effective development of telemetry processing systems capable of meeting the performance requirements facing NASA in the coming decade.

The Telemetry Processing Control Environment (TPCE) provides generic software components designed for controlling and monitoring the operation of the VLSI-based systems developed by GSFC's Data Systems Technology Division. It controls the operation of these systems, provides mechanisms allowing users to monitor their operation, and manages the distribution of telemetry datasets to user sites.

Operation of a telemetry processing system using the TPCE can be automated based on an activity schedule which can be read from an external source (a file or network socket), or manually edited using a GUI. It also provides a display of the activity schedule, and allows the user to add and delete telemetry processing session events and manually initiate telemetry processing, as well. Control of the VLSI systems is accomplished through editable configuration sets, which include parameters used to specify the nature of telemetry processing. Thus, a single VLSI system can support various types of telemetry processing simply by loading different configuration sets.

The TPCE system provides graphical displays that present the status of telemetry processing. These displays are updated dynamically to present data quality information for ongoing telemetry processing sessions, show historical, summary data quality and accounting information for processed sessions, and present the status of VLSI subsystems. The TPCE also automatically generates reports summarizing the quality and accounting information for completed telemetry processing sessions. Telemetry datasets generated by the VLSI systems as the result of processing are automatically collected by the TPCE and distributed to specific user sites using industry-standard network communications protocols such as TCP/IP and ftp. The TPCE provides for queuing of dataset distributions and retransmission of individual datasets upon user request. The TPCE also automatically generates reports summarizing the status of data distribution to user sites. To allow for tailoring the operation of the system without modifying or writing additional software, the TPCE provides a large set of system preferences. To maintain a history of processing activities, the TPCE provides an on-line, viewable log of system events. This event log can also be annotated on-line by the user.

The TPCE runs on Hewlett-Packard graphics workstations under the UNIX operating system. It is composed of a set of UNIX operating-system processes that interact to control and monitor operation of the VLSI-based systems. TPCE provides a windowed user interface based upon the X Window system, and is compliant with the Open Software Foundation's (OSF) Motif user interface style. The entire TPCE system follows an object-oriented design and is implemented using the C++ object-oriented programming language.

The TPCE is designed as a multiprocess system which can be distributed over multiple UNIX workstations. A number of simultaneously executing operating-system processes cooperate and communicate to control and monitor operation of telemetry processing systems. The TPCE may operate on a single host workstation or in a multihost mode, wherein any specific process may be allocated to any one of a number of host workstations. In a particular system being built by NASA GSFC for the SMEX FAST mission, two workstations are configured with the TPCE to support cooperative operation of the

system. One workstation supports control and monitoring; the second supports distribution of datasets to user sites. All user displays from the second workstation appear on the first workstation's monitor; this allows the user to monitor the operation of a multihost system from a single display.

The internal structure of almost every TPCE process is virtually the same. A process contains a series of C++ class objects which are initialized by the process, and then invoked through system-event function callbacks. When some type of system event occurs—a user input, system wall clock time-out, interprocess communication, or file input—a system event is generated, causing a specific, predefined member function of one of the process' classes to be called. This event callback structure is supported by C++ classes which provide general callback capabilities instantiated for specific types of system events. Examples of these C++ classes include *WrEvent*, which provides callbacks based upon user input to TPCE displays, *AlarmClock*, which provides callbacks based on wall clock timers, *IPCServer*, which provides interprocess communication callbacks, and *DataServer*, which provides status and monitoring data to registering objects through callbacks.

The TPCE processes are the largest reusable components of the system. But there are a large number of C++ class components that comprise these processes and which themselves are reusable. This component-level generality provides a framework for combining components to support additional capabilities not currently implemented in the TPCE system. TPCE components include:

- Tape recording, archive, playback, and contents management, as well as tape-drive device control;
- Telemetry data quality and accounting data collection, storage, retrieval, display, reporting, and archival;
- User editing, creation, deletion, and management of libraries of system configuration parameters;

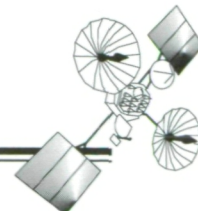
- Operational event logging, including archive, user annotation, and display;
- Schedule ingest, display, storage, and editing;
- Batch, user-initiated telemetry processing;
- System preference parameters, to dynamically change characteristics of system operations;
- Various time types, clocks, and alarms;
- GUI components for the X Window System and OSF Motif and for gathering user input, time, and interprocess communication events;
- Generalized, distributed operating-system process initiation, termination, and management;
- UNIX system services such as file and directory management, ftp, E-mail, pipes, sockets, datagrams, and shared memory; and
- Container objects, such as ordered and unordered lists, dictionaries, and linked lists.

By combining generalized hardware and software components, the TPCE system provides a framework for the cost-effective implementation of telemetry ground systems for existing and future NASA projects.

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Sponsor: Office of Space Communications

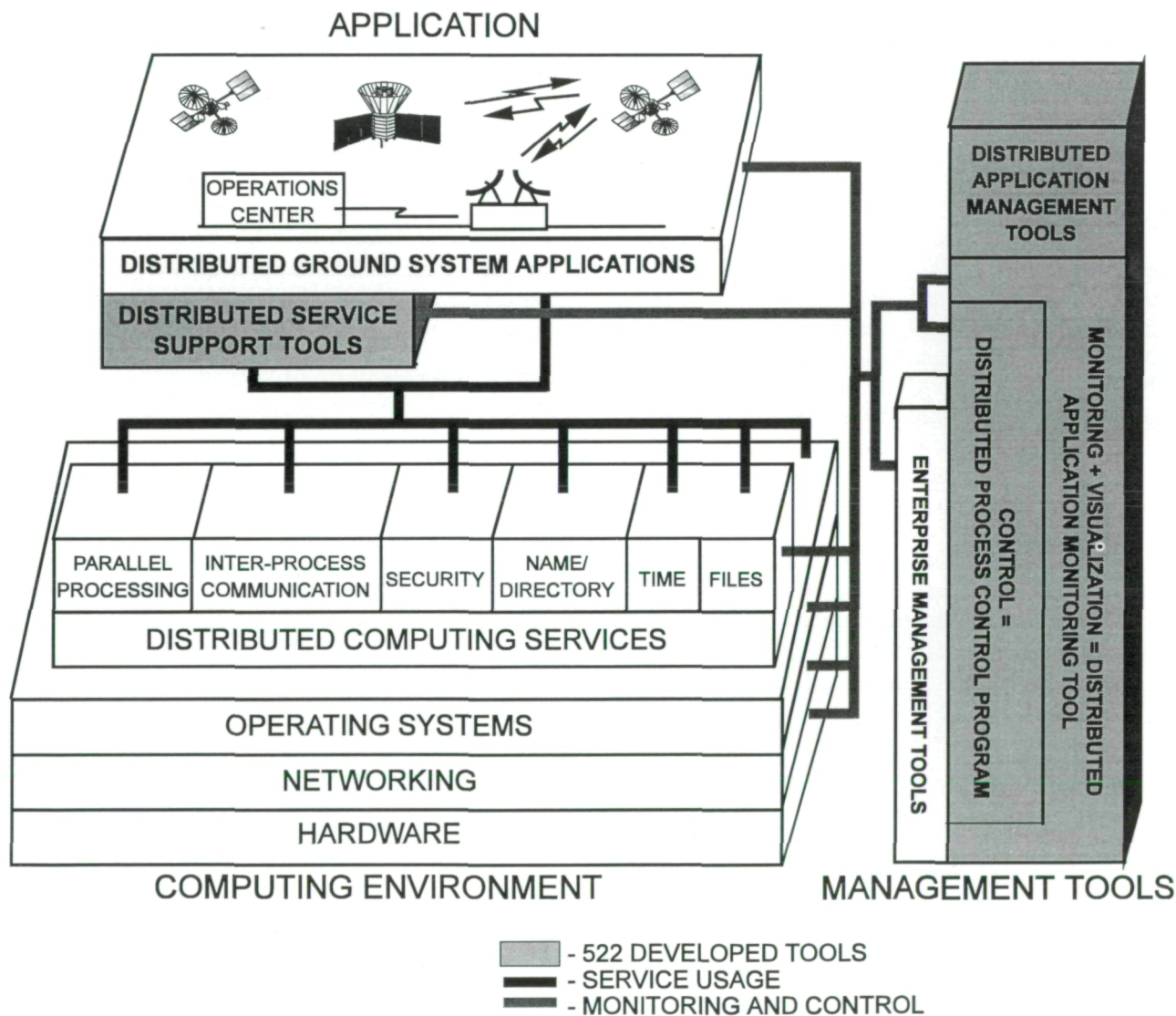
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THE DISTRIBUTED COMPUTING INITIATIVE

DISTRIBUTED, OPEN SYSTEMS technologies will have a major impact on ground systems being developed in the Mission Operations and Data Systems Directorate. Unfortunately, distributed systems are notoriously difficult to develop, test, and control. To help address these difficulties, the Data Systems Technology Division has undertaken the Distributed Computing Ini-

tiative (DCI). The figure illustrates the main elements being addressed by the DCI. To date, the project has developed the Distributed Applications Toolkit (DAT), which consists of two tools: the Distributed Applications Monitor Tool (DAMT), and the Distributed Process Control Program (DPCP). Additional DCI elements will be addressed in FY94 and beyond.



Distributed Computing Initiative.

The DAMT is used to monitor the processing topology and interprocess communications of distributed applications. DAMT is the first such tool that works at the application layer of abstraction. Potential users only need to know the names of processes in their application. The tool automatically locates the processes across their potential hosts, finds any circuits between them, and reports the traffic over these circuits at a user-defined rate. Circuits may be between processes on the same or different machines. The DAMT is unobtrusive (i.e., users do not have to modify their systems or the underlying operating system to use the tool). DAMT is written in C and operates on Sun and Hewlett-Packard platforms under the Motif windowing system. Future versions of the DAMT will provide additional process and circuit information. This information is already available in the operating-system interfaces currently accessed by the tool. DAMT also will be enhanced to monitor multiple physical Local Area Networks (LANs) and will support multiple interprocess communications protocols and methods, including remote procedure calls.

The DPCP helps users manage a set of distributed, interdependent processes. The tool performs four major process-management functions. First, it can automatically start a set of processes across multiple, heterogeneous hosts. Second, DPCP monitors the status of each process in the set; when a process fails, DPCP automatically restarts the process. Third, the tool retrieves any error messages that are generated when a process fails and stores them in a user-specified file. This feature has proven useful in debugging distributed applications. Fourth, the DPCP can automatically shut down the process set. All of these tasks are controlled through a Motif-based user interface on a Unix workstation and are performed using standard Unix tools (e.g., `make`, `ssh`, `rsh`, and `awk`).

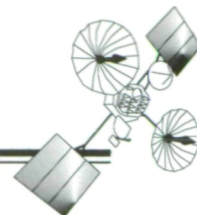
One of the more important features of the DPCP is that it is sensitive to process interdependencies while performing process-management functions. This is particularly important during process start-up and failure recovery. For example, when a process fails, any processes that are dependent on the failed process must be terminated and then restarted after the failed process has been restarted. Users typically find it difficult to remember the potentially numerous interdependencies in even moderately sized, distributed applications. In DPCP, users define their process dependencies and process-to-processor allocations once. DPCP then automatically applies this information to make sure processes are started, terminated, and restarted in the correct order and at the correct location. Currently, the tool supports only static dependencies (e.g., process A must be started before process B). Dynamic dependencies, such as interprocess communications, are not yet monitored by the tool. Future enhancements to DPCP, however, will include support for dynamic dependencies between processes and support for dynamic reallocation of processes to processors.

Tools such as these will allow better utilization of resources across distributed platforms, and make it much easier for users to monitor and control their computing processes.

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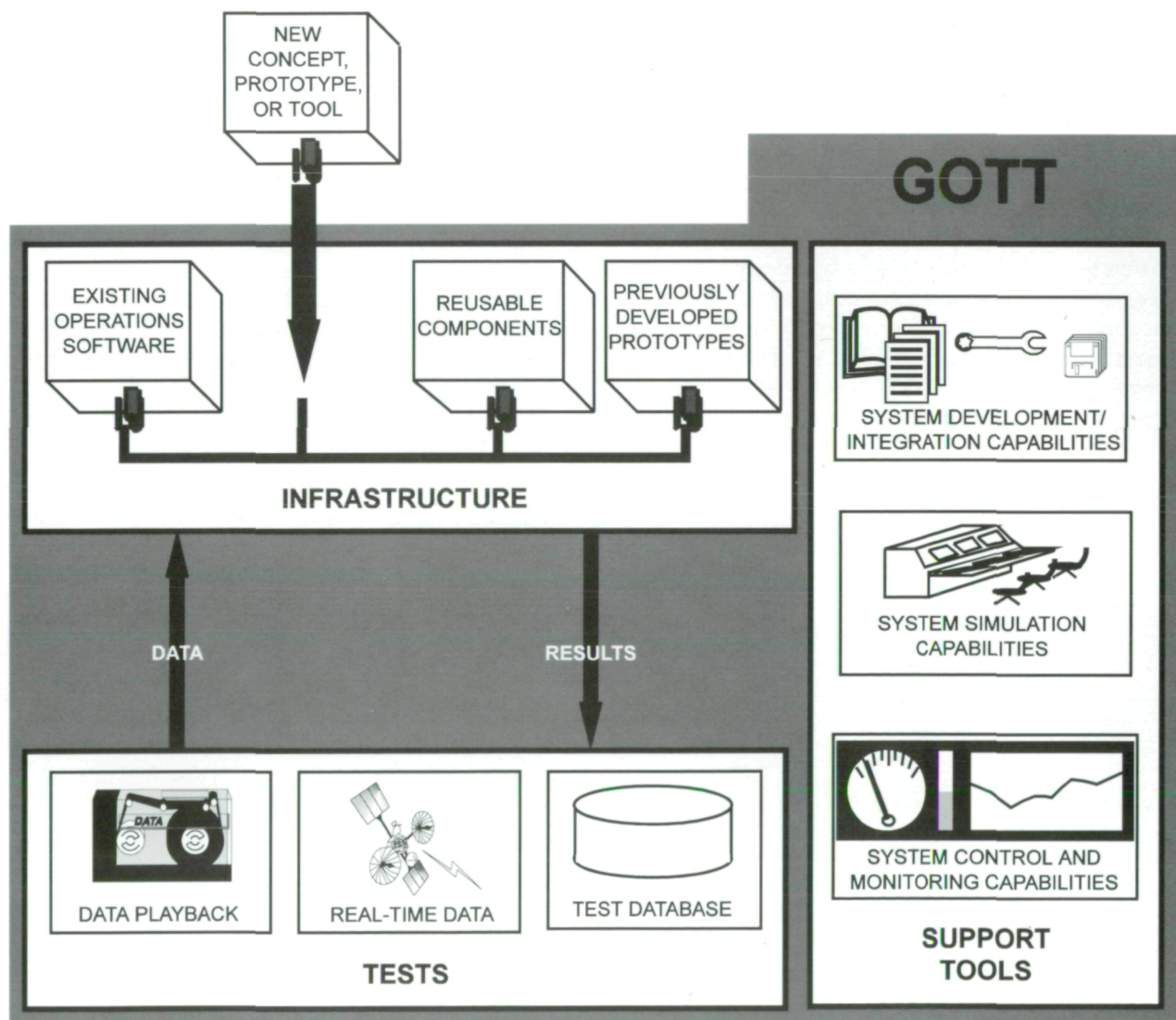


THE GROUND OPERATIONS TECHNOLOGY TESTBED

THE NUMBER OF NEW technologies that can be applied to ground systems has grown steadily over the last few years. Deciding which of these technologies best meet the needs of future ground systems is a difficult and costly task. Furthermore, inappropriate use of technologies can jeopardize mission success and increase maintenance costs. To help address these issues, the Data Systems Technology Division (Code 520) has developed the Ground Operations Technology Testbed (GOTT).

GOTT provides a near-operational environment for the rapid development, demonstration, and assessment of ground-system technologies.

The figure illustrates GOTT's latest capabilities. GOTT's infrastructure includes Code 510's TPOCC software, a set of C++ classes that makes it easier to access the most common TPOCC interfaces, a set of C++ classes that enables a user-interface developer to add speech recogni-



Ground Operations Technology Testbed.

tion and synthesis to a user interface, and a set of reusable TPOCC-based user interfaces and applications that make it easy to provide a realistic context in which to demonstrate a new technology.

GOTT's support tools include automatic code generators for user interface display and dialogue, a mission-independent simulator, and user and system performance monitoring tools. The code generation tools use a method called prespecifications to allow a user to define system elements in terms of established models (e.g., state machines) while still working within the development language (e.g., C++). Using GOTT's Mission-Independent Simulator (GMIS), a user can define, integrate, and control one or more spacecraft system models. The models may be written in TPOCC's command language, C, or C++. The GMIS feeds the results of these models into the TPOCC software as a simulated telemetry stream. GOTT's performance monitoring tools can detect, time-stamp, and display user actions such as keystrokes and mouse actions, and software events.

GOTT's test tools include the simulator described above and an events-management subsystem that can be used to time-order, store, and retrieve events from distributed sources, particularly those from GOTT's performance monitoring tools. In the future, GOTT hopes to add the abilities

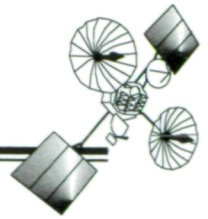
to access real-time telemetry data and to play telemetry tapes at real-time rates. Due to GOTT's near-operational nature, however, a GOTT user can quickly migrate products to the TPOCC Development Facility (TDF), which does provide these real-time data capabilities. GOTT works closely with the TDF to ensure that these transitions are easy and that both facilities have a common tool base.

GOTT already has been used to support several technological developments, including the use of voice recognition and speech synthesis technologies for spacecraft and ground-system monitoring, prototyping of Code 560's next-generation DDF, and the development of Code 520's GenSAA for use by Code 510 and possible use by Code 530. The tools developed to support these projects and the projects themselves have been added to GOTT to provide even greater leverage for the exploration of future technologies.

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FLIGHT SOFTWARE FOR THE COPROCESSOR, HUBBLE SPACE TELESCOPE'S NEW ON-BOARD COMPUTER

THE UPCOMING HST Servicing Mission will involve a number of important repairs and replacements, including the installation of Corrective Optics Space Telescope Axial Replacement (COSTAR), which is designed to compensate for the spherical aberration of the primary mirror. However, there are a number of other important servicing mission support efforts that are not as well-known. One of these is the Coprocessor project.

The Coprocessor is an entirely new computer that will be mated to an existing DF-224 flight computer via a pair of test ports that were used in ground testing, but not during flight. The Coprocessor was developed in response to on-orbit memory unit failures that have occurred in the DF-224. The DF-224 was equipped with six memory units, four of which are required for storage and execution of the DF-224's normal flight software. Unfortunately, two of the six memory units have suffered hard failures since the launch of HST in 1990. Although current functionality of the DF-224 is unimpaired, the lack of backups, coupled with the unexpectedly high failure rate, necessitated installation of new memory units during the servicing mission. In addition, the DF-224, which controls the attitude of the spacecraft and carefully points it at astronomical targets, has little remaining CPU bandwidth to support new functionality. As a result, as long as new memory was being added to the DF-224, it seemed logical to install a new processor at the same time. The CPU that was chosen for the Coprocessor is the Intel 80386, which has already demonstrated its flightworthiness in the SAMPEX mission.

The new memory that will be installed during the servicing mission is called Shared Memory and will be accessible by both the DF-224 and the Coprocessor. The Shared Memory interface will permit interprocessor communications between the two computers, allowing the DF-224 to offload computing tasks to the Coprocessor. Moreover, the Shared Memory interface is the Coprocessor's only link to the outside world. The Coprocessor will not have access to any of the spacecraft's telemetry links. All communications between the Coprocessor and the ground will use the DF-224 as an intermediary. Communications are further complicated because the DF-224 has a 24-bit architecture and the Coprocessor has a 32-bit architecture. This means that the messages sent between the Coprocessor and the ground must be decomposed into

bytes and compacted into 24-bit words for transmission through the DF-224. The DF-224 does not have access to any of the Coprocessor's normal memory, which means that the only way to load new software into the Coprocessor is to get the Coprocessor to put it there itself. Therefore, it became necessary to develop software that would provide a means to load and begin execution of new Coprocessor software. This software package was written by the Flight Software Systems Branch (Code 512) and is called the Bootstrap. The Bootstrap software had to be burned into PROM prior to launch for the Coprocessor's CPU to be useful on orbit. Due to the tight schedule, the Bootstrap would not provide any high-level functionality, but would merely provide a way of installing such functionality at a later time. The Coprocessor Bootstrap Flight Software was written and fully tested in just 6 months, and provides many capabilities in addition to the upgrade path described above. These functions include:

- Diagnostic self-tests (which can be individually enabled or disabled), as follows:
 - Checksum-based validation of bootstrap software burned into PROM;
 - Memory read/write verification of Coprocessor local RAM;
 - Address line verification of Coprocessor local random access memory (RAM);
 - Functional test of the Programmable Interrupt Controller;
 - Functional test of the Programmable Interval Timer;
 - Functional test of the 80387 Math Coprocessor;
 - Functional test of the Direct Memory Access capability.
- A robust command handler that will accept any of the following commands:
 - Memory Load (which writes new memory contents into local RAM);
 - Memory Dump (places memory contents into Shared Memory for the DF-224 to pick up and send to the ground);

- Memory Copy (allows for updating of EEPROM contents);
- Transfer of Control (used to begin executing newly loaded software);
- Save State (stores preselected variable and register contents for debug purposes);
- Register Access (can be used to change the contents of selected Coprocessor registers).
- A task scheduler, which can perform any or all of the following functions at various intervals:
 - Complete memory dump (inserts the contents of Coprocessor local memory in Shared Memory, a piece at a time, for transmission to the ground);
 - Memory monitor (regularly reads out up to nine user-defined 32-bit words of Coprocessor local memory for analysis by the ground);
 - Periodic checksum (performs checksum calculations on up to eight discrete memory areas to ensure that the contents do not change unexpectedly);
 - CPU self-test (regularly verifies that the commonly used set of 80386 instructions is operating as expected).
- A Failsafe Loader—a scaled-down, bare-minimum version of the Bootstrap, designed only to fulfill the upgrade path requirement:

- Full handling of all potential interrupts.

Additionally, the Bootstrap software was designed to avoid all interference or potential interference with the existing DF-224 software. As a result, it can be fully disabled and will not perform any activities unless explicitly instructed to do so.

The bulk of the Bootstrap software was written in the C programming language; a few support modules were written in assembly code. The Bootstrap runs in a stand-alone environment (i.e., there is no operating system).

Future Coprocessor activities will allow it to begin taking over the flight software functionality of the DF-224. It will run VRTX, a commercial real-time operating system.

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EOS DISTRIBUTED PLANNING AND SCHEDULING PROTOTYPE

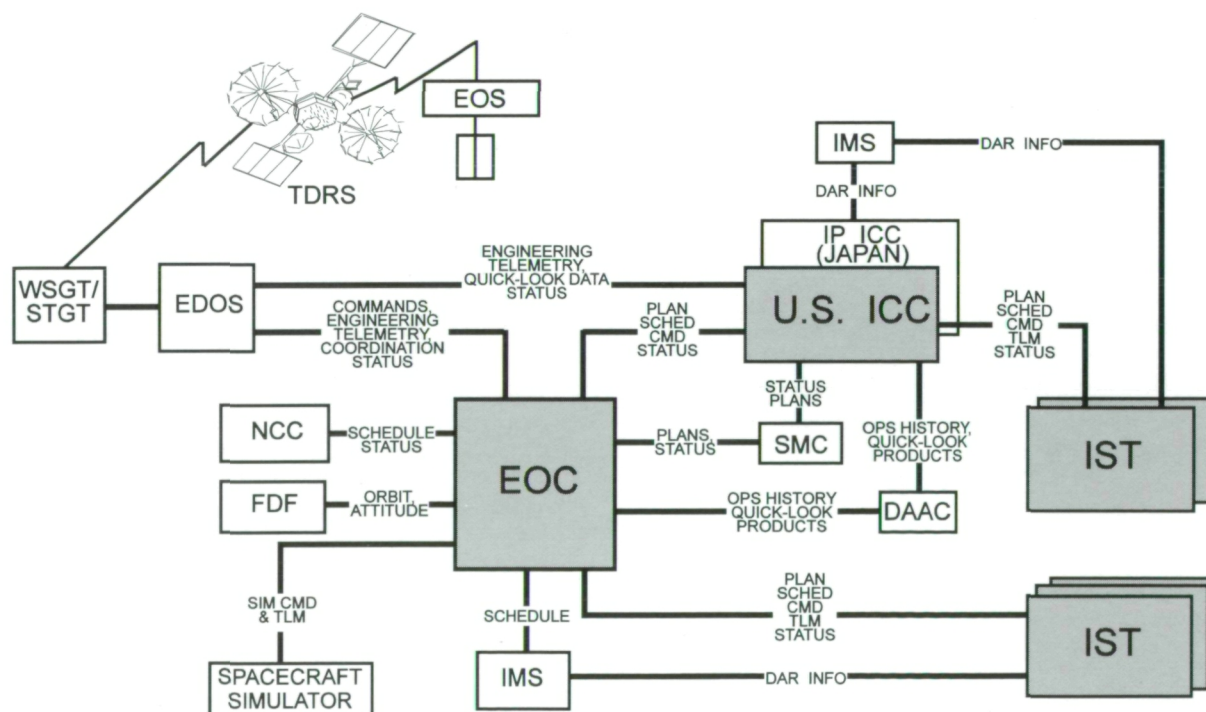
EOS IS AN INTERDISCIPLINARY research mission with the objective of providing the long-term observations and support needed to develop a comprehensive understanding of the global-scale processes that shape and influence the Earth as a natural system.

The EOS mission is assumed to be largely preplanned. The EOS series of spacecraft will be in Sun-synchronous polar orbits that repeat their orbit path every 16 days. Most of the instruments will have a routine operations profile. Some will operate on orbit-related cycles such as spacecraft day/night. EOS instruments will be controlled either from the EOS Operations Center (EOC)—collocated with the spacecraft control function—or from a geographically distributed Instrument Control Center (ICC). An Instrument Support Terminal (IST) allows the Principal Investigator, Team Leader, or instrument engineering team to access any information associated with the operation of their instrument from their local site. The Flight Operations Segment (FOS) is responsible for the operation

of the EOS flight elements, including planning and scheduling of both spacecraft and instruments. FOS comprises the EOC, ICCs, and ISTs for each instrument, as depicted in the figure.

FOS planning and scheduling have the objective of producing a detailed schedule for the activities of the spacecraft and its instruments. The EOS spacecraft and instruments will be designed with the goal that there be little or no contention for resources (i.e., sufficient resources will exist for instruments operating in their routine modes). FOS planning and scheduling will be primarily a management task—particularly for instruments with variable activities—and a coordination effort involving these instruments, data volume, and TDRSS communications support.

The primary goal of the EOS Distributed Planning and Scheduling Prototype—a joint effort between GSFC, the Jet Propulsion Laboratory (JPL), and the University of



SHADED AREAS REPRESENT FOS

EOS Data and Information System.

Colorado's Laboratory for Atmospheric and Space Physics—was to assess the planning and scheduling operations concept for the FOS of the EOS Data and Information System (EOSDIS). The assessment included evaluation of the functions of the distributed planning and scheduling system and definition of the data elements required to support planning and scheduling. In the EOS Distributed Planning and Scheduling Prototype, the EOC is located at GSFC, an ICC is located at JPL, two independent ISTs are located at the University of Colorado's Laboratory for Atmospheric and Space Physics, a third IST is located at GSFC. The prototype answered questions, uncovered and resolved issues buried in the concept, and provided a number of important lessons.

In 1993, three significant lessons were learned in developing the prototype and evaluating the planning and scheduling concept given in the EOSDIS FOS Operations Concept Document (Revision 2). Inasmuch as the FOS has evolved and continues to evolve, some details may not apply to the current version of the planning and scheduling concept.

(1) Need for a Central Scheduler not demonstrated—The FOS planning and scheduling concept assumed a central scheduler at the EOC, but the distributed structure of the prototype and successful scenario operations failed to prove the need for a central scheduler. The questions remaining are: What really is a central scheduler, and what is its role in distributed scheduling? Do the collection and integration of subsystem or instrument schedules really involve scheduling?

The current FOS operations concept reduces as much as possible the amount of interaction among instruments and spacecraft subsystems. A central scheduler makes scheduling decisions that manage interactions to ensure coordination and avoid conflict. It is the complexity of these interactions and the role of the central scheduler in managing them that define the precise requirements for the central scheduler. However, if all instrument scheduling decisions are made by ICCs or ISTs, no central scheduling is taking place. Simple central coordination, such as coordination for orbit adjust maneuvers, can be handled without a central scheduler by distributing the appropriate timing information to the ICCs and ISTs.

In general, only the node scheduling a given instrument or spacecraft operations makes changes to that component's schedule. Each operational scenario for the

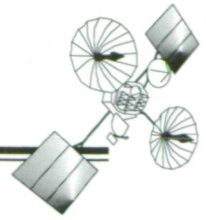
prototype had an option that conformed to this paradigm. All of these scenarios could be performed when visibility into conflicts was available at the node resolving each given conflict. The implication is that a central scheduler may not be needed.

(2) Distributing scheduling processes is feasible and appropriate—The FOS operations concept paints in broad strokes an overview of a distributed scheduling process for EOS. In light of the concept, the prototype and technology readiness evidenced in the prototype, the mapping of scheduling and conflict-resolution responsibility across the nodes of the EOS distributed scheduling system was shown to be both feasible and appropriate. The proposed mapping distributes scheduling responsibility across the entire system, defines a tradeoff between scheduling complexity and iteration, and does not require the incorporation of not-yet-demonstrated technology.

Key mapping features are:

- Complex instrument scheduling is mostly accomplished at the ICC/IST with slidable flexibility for pointing instrument slews;
- All nodes have full visibility into inter-instrument contention for resource and environmental rights (e.g., vibration, thermal, electromagnetic);
- The EOC assigns, by activity, initial action responsibility for conflict resolution to a node that is party to the conflict (this may be done by convention or upon consideration of factors such as priority and flexibility); and
- Most inter-instrument conflicts are resolved by the ICCs and ISTs during an intermediate scheduling phase while the EOC is negotiating a TDRSS schedule.

(3) Use of a distributed database approach may be appropriate—Since every node of the prototype had to store the scheduling information that it needed, there was a significant duplication of scheduling data within the prototype. There was also the need to have a communications protocol that could transfer scheduling information from one node to another. A reasonable question is: could this duplication and transfer of data be reduced or avoided if the nodes used a uniform, distributed database to store scheduling information? We believe a database approach may be appropriate and useful under certain conditions.



To use a distributed database approach to store and access scheduling information, we would have needed to devise a common schema for at least the portion of the scheduling database shared by more than one node. There is little doubt that by implementing a distributed database with a common schema, duplication of scheduling data could be reduced. It would also likely be easier to modify the common schema and to allow alternative views of scheduling data. However, with current database technology, it is not particularly easy to build and maintain uniform, distributed databases. It is even more difficult when users of the database system have very different needs for, and views of, the data. There is also an implicit limitation here. A uniform, distributed scheduling database would require a common schema that would in turn require a significant degree of uniformity in the representation of scheduling data at each node; but for large applications like EOS, such uniformity at all nodes may not be practical or desirable. There is a need to further examine geographically dispersed scheduling to determine whether a uniform, distributed database approach might be appropriate. In examining the database approach, care should be taken not to artificially constrain the planning and scheduling problem in ways that make it difficult for sci-

entists and engineers to create and view their own schedules.

Evaluation of the concept and complete findings from the prototyping effort are available in an informal document. Copies of the Earth Observing System Distributed Planning and Scheduling Prototype Lessons Learned Working Paper may be obtained from the EOS Library at NASA/GSFC.

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Sponsor: Office of Mission to Planet Earth

Mr. Hull is a senior computer engineer in the Data Systems Technology Division at GSFC. He has over 25 years of NASA experience in areas as diverse as real-time operational support for manned and unmanned spaceflight missions, computer performance and capacity management, discrete event simulation of computer and communications systems, expert systems, activity scheduling and project management. His current research interests include geographically distributed mission operations, prototyping and genetic programming.

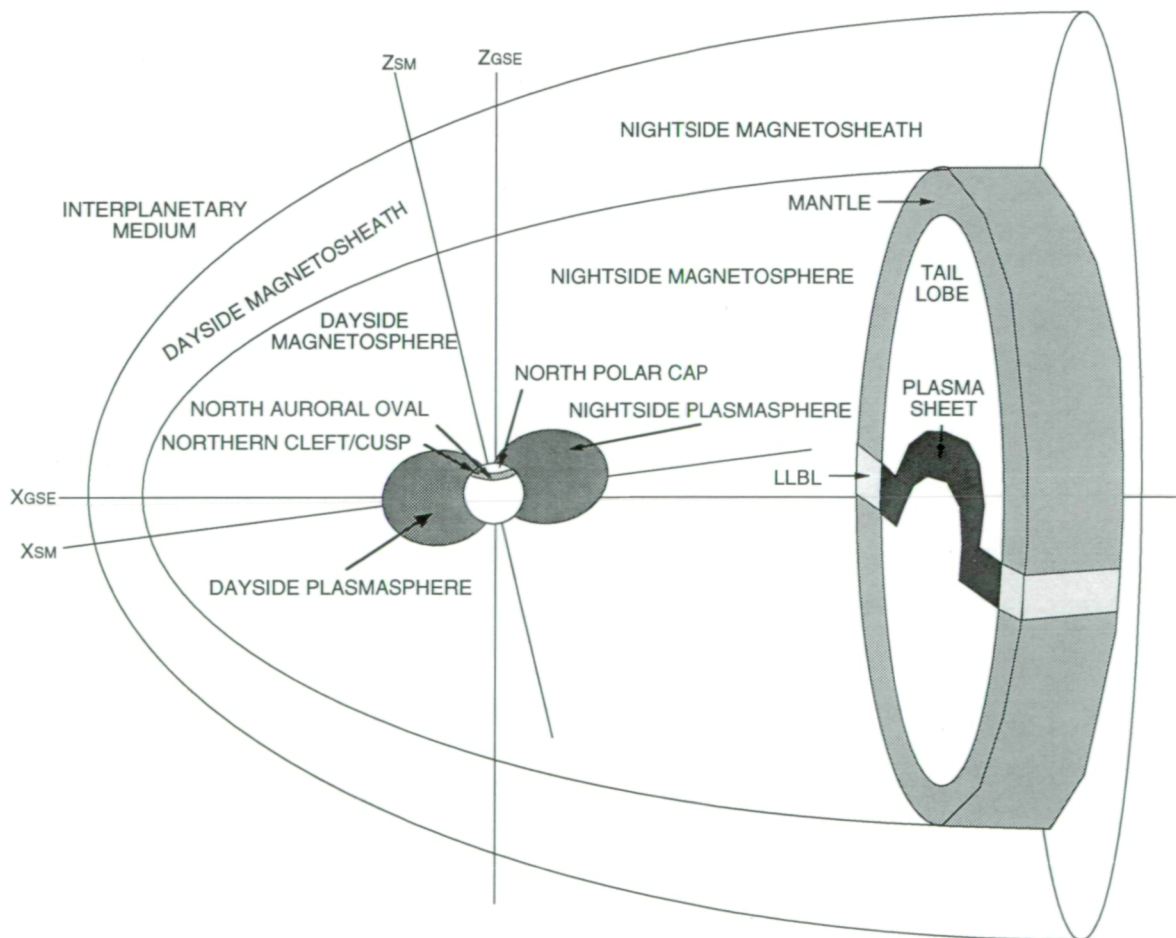
SCIENCE PLANNING SOFTWARE GOES ONLINE

A PRIMARY THEME in NASA and international space-physics programs of the 1990s is the acquisition and analysis of data received simultaneously from multiple spacecraft and ground-based observations. These combined data are key to better understanding the global, 3-dimensional, and dynamic structure and physics of the Earth's magnetosphere and its interactions with the Sun. These topics are the focus of the ISTP program and the InterAgency Consultative Group (IACG) Solar Terrestrial Physics (IASTP) initiative.

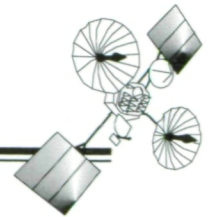
The Earth's magnetosphere consists of regions and boundaries between regions characterized by distinct

plasma properties (composition, densities, distribution in energies), field properties (magnetic and electric field strengths, and field-line configurations) and physical processes, as illustrated in the first figure. These regions are closely coupled in their interactions and have a complex 3-dimensional topology. A key issue in acquiring the right new data from experiments that are part of missions such as ISTP, and in initially understanding such data once acquired, is to identify times when, for example,

- a given spacecraft is expected to be in given magnetospheric regions;



Earth's magnetosphere showing some key plasma and field regions of interest to science mission planners.



- multiple spacecraft are predicted to be in a particular configuration;
- spacecraft are aligned with each other along lines of the magnetic field.

It has been the mission of the operational Satellite Situation Center (SSC), and the purpose in developing new versions of its primary software system, to enable the effective combination of spacecraft location information with the latest region and field models to usefully answer questions such as those above. The SSC was formed as an element of the National Space Science Data Center (NSSDC) in the mid-1970s. It has supported a range of programs, including the International Magnetospheric Study (IMS) in the late 1970s, Dynamics Explorer science planning and operations, the Polar Regions Outer Magnetospheric International Study (PROMIS) campaign in 1986, and Coordinated Data Analysis Workshops (CDAWs).

In the last few years, the Space Physics Data Facility (SPDF) has conducted a major effort to upgrade the SSC software system. As a joint NSSDC and SPDF effort, this system is now publicly accessible via Internet and the DECnet Internet, and will be available for prototype distribution to the working science community for installation on their own computing platforms.

SSC system elements include:

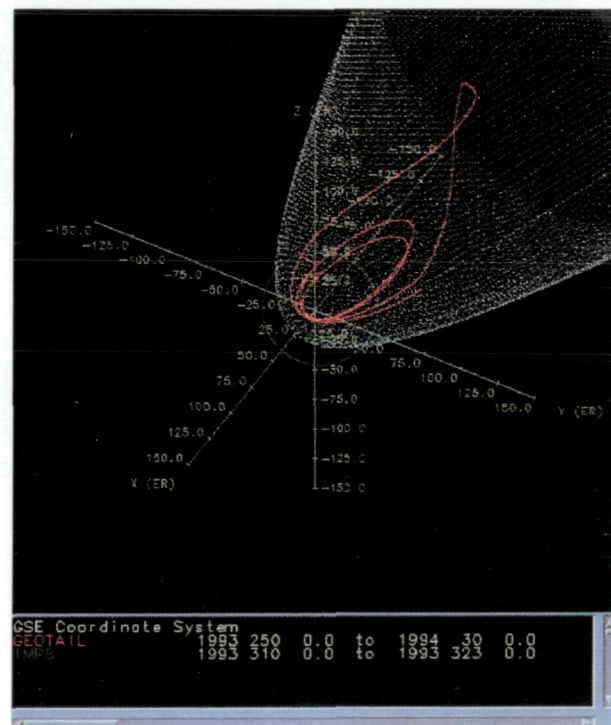
- The Locator subsystem, whose purpose is to provide highly customizable tabular and graphical outputs showing spacecraft location;
- The Query subsystem, whose purpose is to generate lists of times when spacecraft satisfy specific constraints on the regions they occupy and/or the extent they may be connected to each other or to specified ground sites along lines of the ambient magnetic field; and,
- Other system elements, whose purpose (along with various utility functions) is to calculate and display conversions among various geophysical coordinate systems and magnetic field-line footprints from specific spatial locations.

Tabular output from Locator allows a spacecraft's coordinate location to be listed in a variety of systems, as well as other location-related items. These include parameters

such as: magnetic field-line footprints; magnetospheric region; distances from the spacecraft to various regions; and the L-value, magnetic field strength, and invariant latitude at the coordinate location of the spacecraft.

The Locator subsystem can provide graphical output as a three-dimensional plot of spacecraft trajectories. The graphics user may: change the view angle and zoom factor, project spacecraft trajectories to a coordinate plane, display selected magnetospheric regions, and label points along the satellites' trajectories. The second figure is a sample of such graphical output. These graphics are standard-based using PHIGS (Programmer's Hierarchical Interactive Graphics System) and PEX (PHIGS Extensions under X).

The Query subsystem presently provides two primary query-matching scenarios: magnetospheric region occupancy and magnetic field-line tracing. The region query lists the entry and exit times during which specified satellite(s) were in particular magnetospheric regions. The



A sample 3-dimensional graphical output from Locator, showing a view of Geotail's orbit from September 1993 through January 1994, along with a single orbit of IMP-8 in November 1993. A model bowshock is superimposed.

trace query identifies either periods when one or more spacecraft are in the same magnetic flux tube of force as a specified lead spacecraft, or periods when one or more spacecraft occupy a field line which traces down to a specified ground station.

Any computational and display software system supporting science planning and subsequent data analysis is effectively useless without an adequate and current database of spacecraft predictive and definitive ephemeris data. The on-line system is tied directly to the same database used and maintained by the operational SSC itself, which presently covers some 33 past, present, and future NASA (and other) spacecraft. The system is designed to support a mode where the intermediate files generated in the process of updating the SSC database itself can also be transferred to other sites that may be operating the SSC software for spacecraft of interest to a given site. The software is presently supported on Sun workstations and VAX/VMS machines. To access the on-line system, users should connect to one of the machines in the NSSDC cluster (e.g., NSSDCA under DECnet or nssdca.gsfc.nasa.gov under TCP/IP and the Internet) and then log on to the NODIS

public account. The SSC system is accessible under the new NODIS interface as a sub-option of the Space Physics menu.

A primary issue over the next year will be to assure all key functionality required by ISTEP and the ISTEP SPOF are identified and addressed, as well as any other requirements that may arise as plans to support the IASTP international effort evolve.

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Sponsor: Office of Space Science

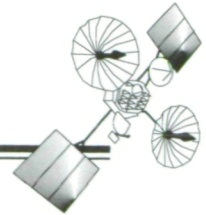
Dr. Robert McGuire is a physicist and Head of the Space Physics Data Facility. He presently leads the SSC upgrade effort.

Dr. Mauricio Peredo is a Hughes STX physicist who presently is part of the ISTEP Science Planning and Operations Facility (SPOF) team. He has played a critical role in adaptation and integration of current geophysical models into the SSC software.

Ms. Lara Aist-Sagara is a Hughes STX computer scientist and graphics expert who currently heads the SSC software development task and has had the key technical role in the initial PHIGS/PEX-based SSC graphics software development.

Dr. Sardi Parthasarathy is a Hughes STX physicist who heads the operational SSC. He is a Professor Emeritus at the University of Alaska.

Start Time			Stop Time			Sat.	Region
yyyy	ddd	hh:mm	yyyy	ddd	hh:mm		
1993	299	18:36	1993	306	10:48	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	312	05:48	1993	315	19:36	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	315	19:48	1993	315	21:24	GEOTAIL IMP8	Plasma Sh Intpl Med
1993	315	21:36	1993	316	18:12	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	316	18:24	1993	316	22:48	GEOTAIL IMP8	Plasma Sh Intpl Med
1993	316	23:00	1993	317	17:12	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	317	17:24	1993	317	23:36	GEOTAIL IMP8	Plasma Sh Intpl Med
1993	317	23:48	1993	318	16:24	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	318	16:36	1993	319	00:24	GEOTAIL IMP8	Plasma Sh Intpl Med
1993	319	00:36	1993	319	04:36	GEOTAIL IMP8	Tail Lobe Intpl Med
1993	324	14:00	1993	325	04:00	GEOTAIL IMP8	Plasma Sh Intpl Med



REQUEST-ORIENTED SCHEDULING ENGINE

SCHEDULING INVOLVES placing activities on a timeline, subject to resource and timing constraints. An activity may require the use of one or more resources at the same time, so scheduling algorithms check to see if adequate resources can be allocated to the activity. Timing constraints can be defined with respect to the time of day, user-defined events, and other activities.

The Request-Oriented Scheduling Engine (ROSE) is a scheduling system developed by the Data Systems Technology Division at GSFC. ROSE contains sophisticated software technology, including a high-level scheduling language, a rescheduling algorithm based on artificial intelligence (AI) technology, and a graphical user interface built on the Transportable Applications Environment (TAE) Plus. ROSE is written in the Ada programming language. ROSE was submitted to COSMIC, the distributor of NASA-developed software to government, industry and other organizations in June 1993.

ROSE has a scheduling language called the Flexible Envelope Request Notation (FERN). The FERN language has data structures that represent user requests, user activities, available resources, time events, and timing relationships between items. FERN allows users to define new items that use the specifications of existing items so that users may work with their own terminology. By using the FERN language, the need to write new software code is reduced or eliminated. FERN language statements are processed as input data. For example, a new resource, such as a crew member, can be added to the FERN data files without having to recompile any software code.

ROSE provides batch scheduling with various request selection and placement heuristics. It also supports interactive scheduling by providing the user with information on resource conflicts, resource usage, and timing constraints. In both the batch and interactive scheduling modes, ROSE updates the graphical display so that the user may observe the schedule being built.

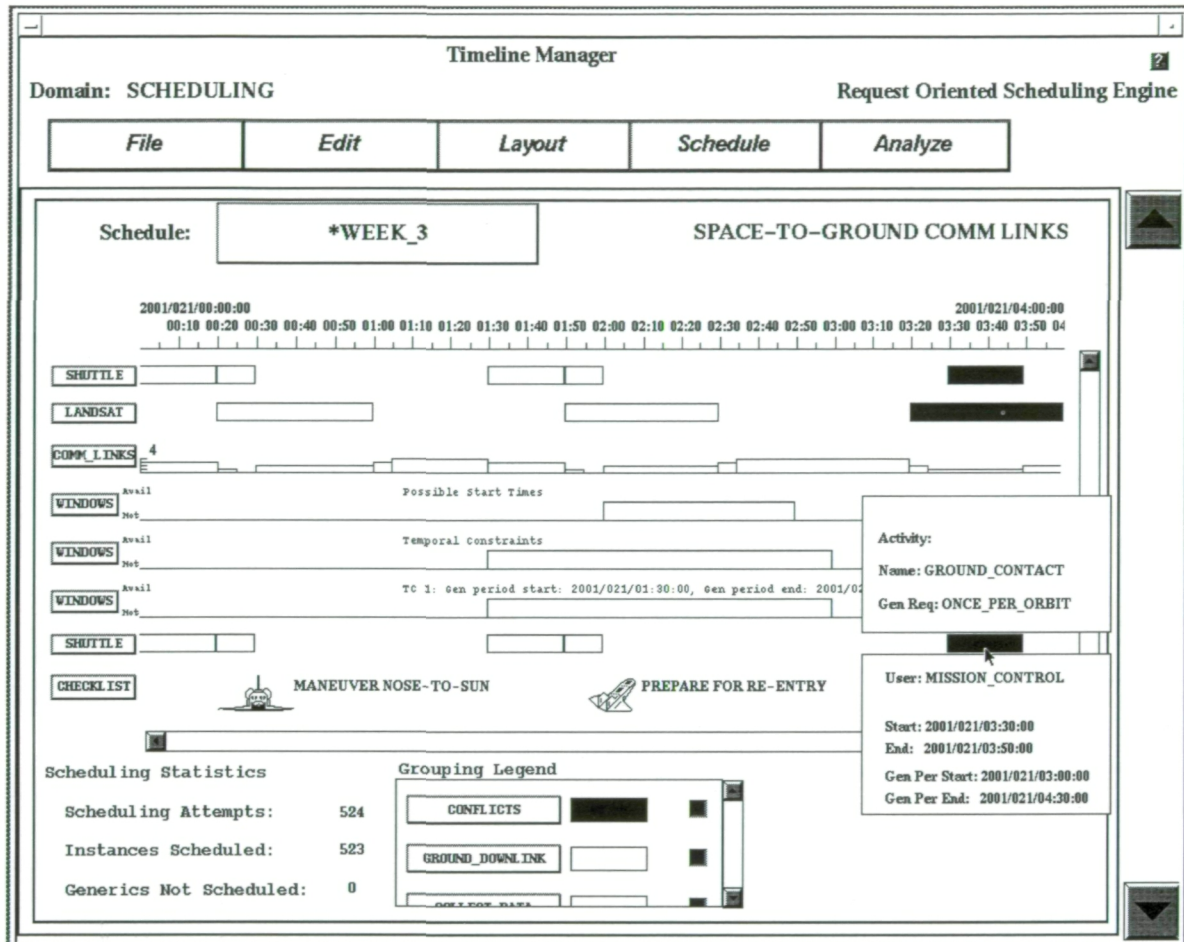
There are four types of graphical timeline plots provided in ROSE (see the figure). An Activity plot displays activities that use a particular resource. A Resource plot shows the remaining amount of a resource that is available for allocation. A Step plot displays detailed information about items that comprise an activity, using both

graphical symbols and text. Lastly, the Possible Start Times plot contains a plot of each resource and timing constraint that contributes to the placement of an activity on the schedule so that scheduling conflicts can be analyzed. A grouping and marking capability allows the user to organize activities according to user-specified criteria. A group is a collection of zero or more activities and is marked with a user-designated color. The user can move, delete, edit, or reschedule all activities in the group as a single entity. Using the ROSE interactive interface, the user can control the execution of the scheduling algorithms and make changes midstream. Also, the user can manually reschedule an activity by dragging it along the graphical timeline while ROSE highlights in orange the activities that are in conflict as immediate feedback.

ROSE has a rescheduling algorithm that uses a classical AI technique called Best-First Search. The algorithm is written in Ada, and it employs heuristics and evaluation functions to control and limit the search for rescheduling solutions. Since ROSE is a general tool that can be tailored to solve many types of scheduling problems, scheduling heuristics and algorithms can be added to it. By modifying or adding new scheduling heuristics, a user can adapt ROSE to the unique needs of a new application.

ROSE is currently being used in a proof-of-concept for flexible scheduling for NASA's Space Network (SN), a student pilot training system for the U.S. Air Force, and NASA ground-station loading studies for satellite communications. The SN application is interesting in that ROSE has been used in benchmark testing to assess the value of flexible scheduling to the problem of scheduling TDRSS resources.

The ROSE benchmark has demonstrated that the added flexibility requires two to three times as much processing time (i.e., a difference of about 18 versus 10 minutes for a run of about 3,000 events). However, the number of events scheduled increased by about 15 percent with flexibility compared to processing without flexibility. The Networks and Data Systems Technology Divisions are now working on a detailed proof-of-concept activity to evaluate flexible scheduling technology as implemented in ROSE. Key to acceptance by operations is the proof that ROSE performs at least as well as the current system, and that the



ROSE Timeline Manager Screen.

new technology demonstrates clear benefits. For SN operations, a reusable scheduling tool with built-in flexibility translates into the ability to support an evolving and diverse mission-support load without increasing operational complexity and cost.

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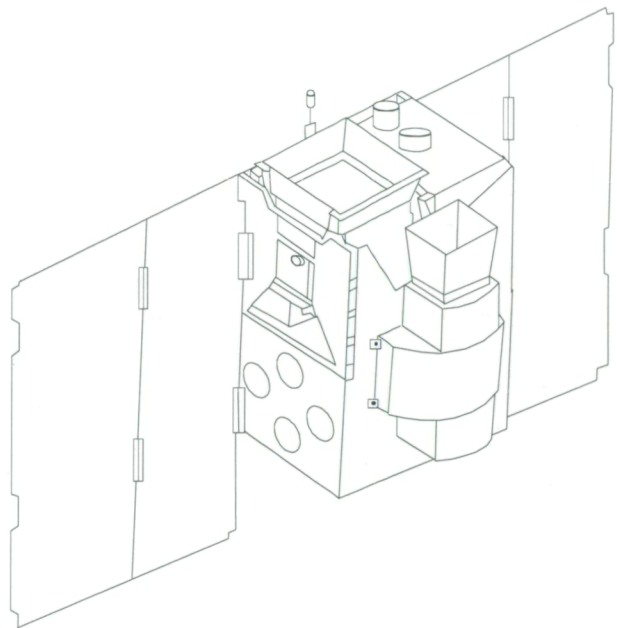
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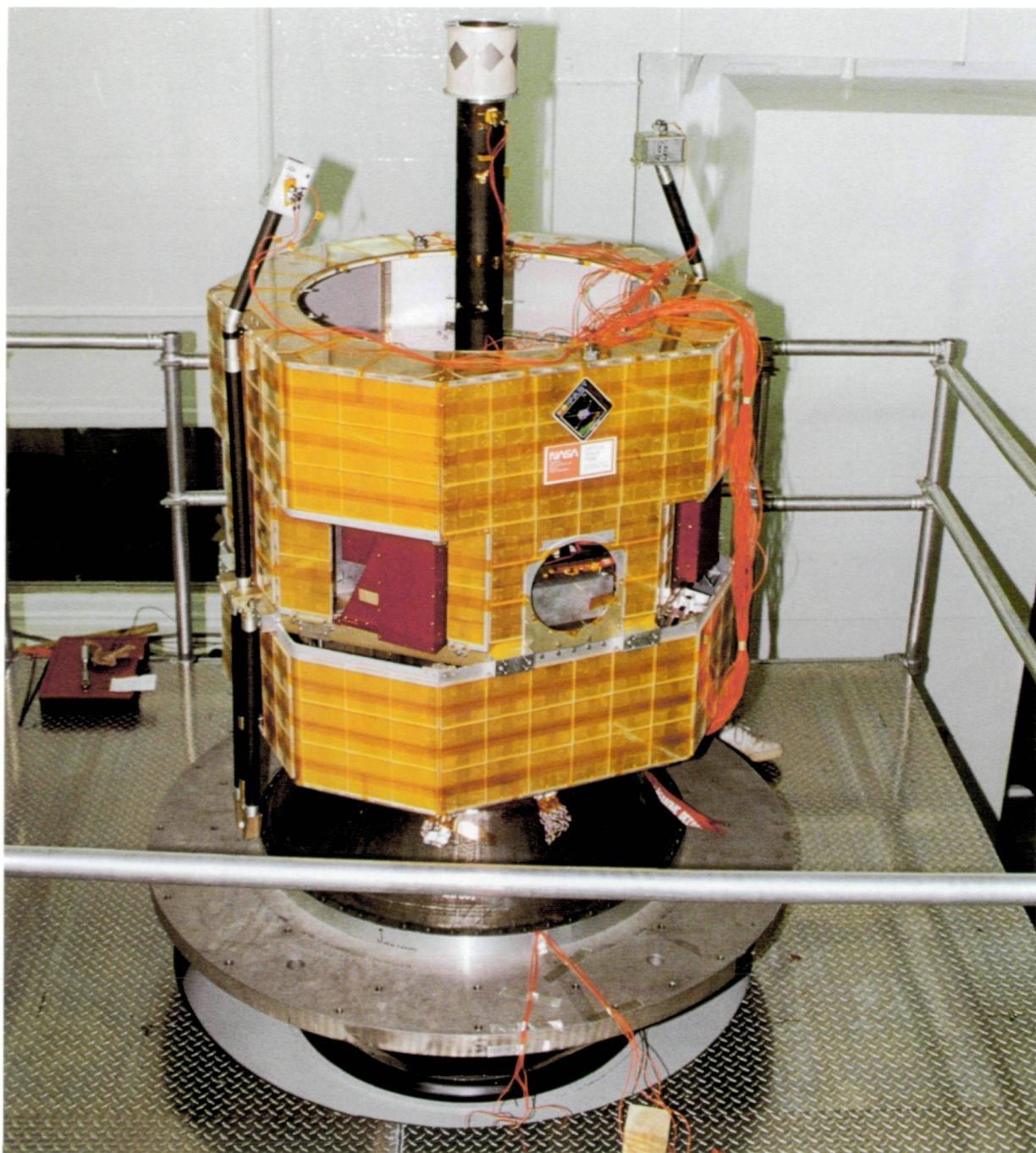
Sponsor: Office of Space Communications

Ms. Karen Moe has been at GSFC for 20 years and recently has served as the Manager for the Space Network prototyping activities. She received her MS in Electrical Engineering from the University of Maryland in 1978.

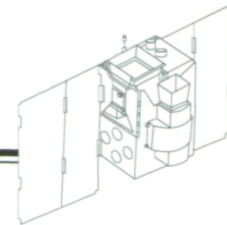
Mr. Michael Tong received his BS in Engineering from Tufts University. Currently, he is working on software planning and scheduling concepts. Mr. Tong has been with GSFC for 18 years.

ENGINEERING AND MATERIALS





The Engineering Test (ETU) of the Fast Auroral Snapshot (FAST) spacecraft is shown in the photograph above. The FAST mission is the second in a series of Small Explorer (SMEX) satellites designed and built in the Engineering Directorate at the Goddard Space Flight Center. FAST will explore the microphysics of the auroral acceleration region using electric field, magnetic field, and particle instruments that are designed to take extremely high-time-resolution "snapshots" of a wide range of fascinating plasma phenomena that occur between 1,000 and 4,000 km in the Earth's high-latitude "auroral zones." In this photograph, the satellite is being readied for environmental testing. The yellow areas represent the solar array, the tube extending from the top of the satellite is the antenna support, and the small, folded tubes are the deployable magnetometer booms. FAST is scheduled for launch in August 1994, on a Pegasus XL spacecraft.



ENGINEERING AND MATERIALS

THE ENGINEERING DIRECTORATE supports NASA Space and Earth Sciences flight projects and applications programs through technical research and development. The Directorate's enabling technology program increases knowledge and capabilities in areas necessary for the success of assigned NASA missions. An important part of its mission is the design, development, and testing of systems, subsystems, instruments, components, and spacecraft for multiple programs and projects. In addition, the Directorate oversees the in-house and contractual development of flight hardware and software, including instruments, attached Shuttle payloads, and small Explorer spacecraft. The Directorate also provides system and discipline engineering support for such space and Earth Science missions as the Hubble Space Telescope and the Earth Observing System.

Current activities include: technology research in laser communications and sensing, cryogenics, sensors, thermal systems, and spaceborne data systems; instrument development for the Cassini Planetary Mission, the Advanced X-ray Astrophysics Facility, and the X-ray Timing Explorer; development of payload modules and spacecraft for the Tropical Rainfall Measuring Mission and the X-ray Timing Explorer; Small Explorer satellite programs for frequent astrophysics missions; and application of new materials and manufacturing techniques.

To these ends, the Engineering Directorate is organized around five operating divisions which support the Goddard space and Earth science missions in low-Earth orbit.

The Space Technology Division provides the Center with the technical skills necessary for design, development, and management of spacecraft and instrument components, and subsystems such as guidance, attitude control, cryogenics, propulsion, and fluid, photonic, and optical systems. The Division is responsible for the design and development of flight automation and robotic systems. It also plans, maintains, enhances, and operates the Robotics Development Facility and the associated engineering test-bed robotic system. The Division devises on-chip data processing techniques and designs and manufactures a

variety of microelectronics devices, solid-state detectors, and integrated and hybrid circuits. It also maintains a capability to support in-house instrument and spacecraft projects and conducts research and development to improve performance and reliability and to reduce the cost of space systems.

The Mechanical Systems Division provides multidisciplinary capabilities needed to design, fabricate, test, and launch spacecraft structural, thermal, optomechanical, and electromechanical systems and subsystems. The Division performs the mechanical design, analysis, development, integration, and test of major structural and deployable mechanical and electromechanical subsystems, including thermal design, development, integration, and test of spacecraft and instrument thermal subsystems. It is also responsible for contamination analysis, evaluation, and protection of critical instrument and spacecraft components and surfaces, and maintains an active research-and-development program through ground-based and in-flight experiments to advance the state-of-the-art in relevant materials, devices, mechanisms, and components. It also provides technical oversight, evaluation, consultation, and support to flight projects, instrument developers, design review teams, failure analysis teams, technical evaluation panels, and source evaluation boards.

The Electrical Engineering Division provides the Center with technical design, development, and management of spacecraft and instrument electrical components and subsystems such as: spacecraft power and data systems; radio frequency, microwave, and millimeter-wave communications; and instruments, advanced space systems and components. It also provides the skills necessary to electrically integrate and test instrument and spacecraft components and subsystems, and performs systems engineering, study, design, development, and analysis functions. The Division designs and develops electrical systems and electrical integration schemes for payload, ground, and flight interfaces; system-level electrical and computer-based ground-support equipment; and the software needed to develop, integrate, test, and launch in-house instruments and spacecraft.

The *Special Payloads Division* provides the management for the Small Explorer Program and for Shuttle payload activities, such as the Hitchhiker, Spartan, Get-Away-Special (GAS) projects, and for other attached payloads that use GAS hardware and concepts. This encompasses activities from project conception through integration and launch in support of both scientific and applications research payloads employing the Scout-class expendable launch vehicles and the Space Shuttle.

The *Engineering Services Division* provides the Center with comprehensive capabilities in the physical sciences, test and evaluation, and engineering, and facilities to support the analyses, design development, fabrication, mechanical integration testing, and launch of spacecraft and instruments. These capabilities cover the broad fields of materials, coatings, fabrication, and environmental simulation.

OFFICE OF FLIGHT ASSURANCE

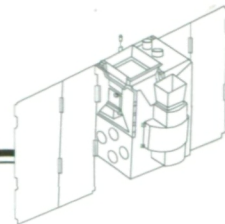
The Office of Flight Assurance is responsible for the technical and flight safety aspects of all GSFC projects, spacecraft systems, launch vehicle systems, operational ground systems, and scientific instruments for both conventional satellites and Shuttle payloads to assure that these systems meet the Center's goals for mission success and reliability. The Directorate also provides guidance to GSFC-managed spaceflight programs by formulating general policy in the areas of hardware and software quality assurance, materials control, parts control, environmental testing, reliability, and flight safety. The Office provides support to GSFC projects in implementing quality-assurance parts and materials selection,

development and control, and systems safety. It also provides expertise to GSFC projects for the solution of materials and contamination problems involving spacecraft and spaceflight hardware.

SUBORBITAL PROJECTS AND OPERATIONS DIRECTORATE

The Suborbital Projects and Operations Directorate manages NASA's Suborbital Sounding Rocket Projects from mission and flight planning to landing and recovery, including: payload and payload carrier design, development, fabrication, and testing; experiment management support; launch operations; and tracking and data acquisition. It is also responsible for managing the technical activities associated with the NASA Balloon Program, providing scientific payloads, support systems, instrumentation, data acquisition, and data processing relating to approved applications missions. The Directorate plans and conducts launches of spacecraft, scientific payloads, and other aeronautical tests and research and development activities for other elements of NASA, the Department of Defense, other Government agencies, and the world scientific community. It also plans and operates suborbital and test flight ranges, associated aircraft, and research airports in support of NASA aerospace programs as well as those of the Department of Defense, other government agencies, and the academic and international communities. The Directorate develops and provides facilities supporting instrumentation and techniques of tracking, data acquisition and handling (storage, retrieval, display, and reduction) used in conducting research projects or tests. It also assists and trains foreign-national scientists in launch support.

Walter B. Sullivan



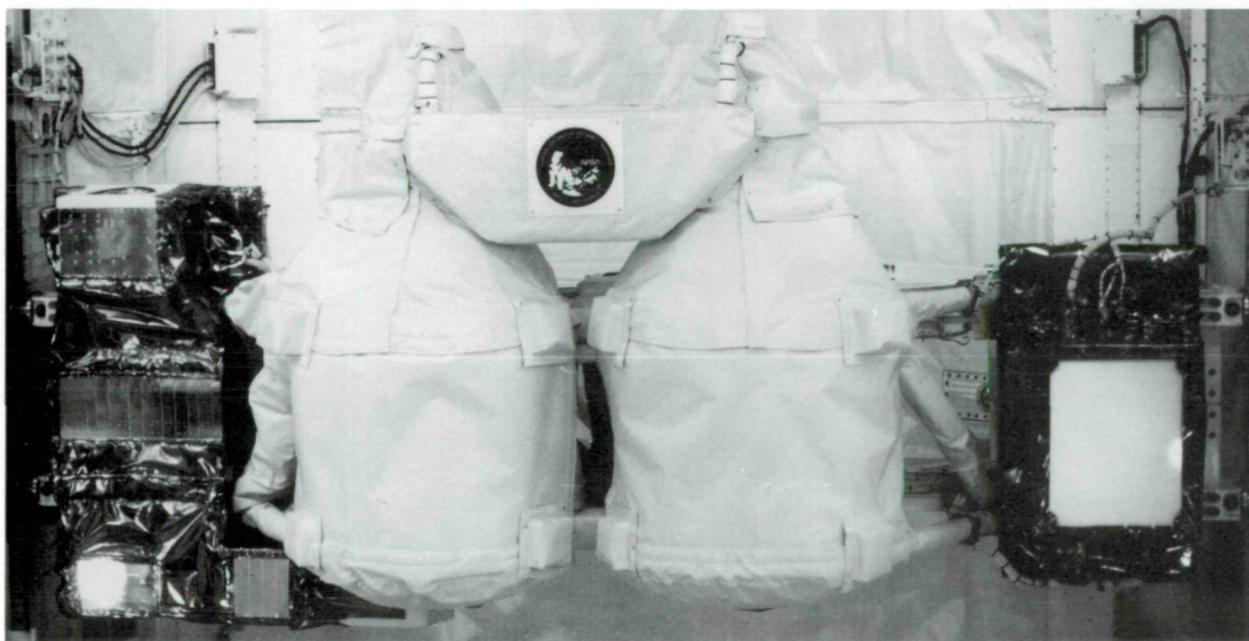
THE SUPERFLUID HELIUM ON-ORBIT TRANSFER FLIGHT DEMONSTRATION

THE SUPERFLUID HELIUM On-Orbit Transfer (SHOOT) Project objectives are to demonstrate the technology required for superfluid helium transfer in space. Another benefit of the program is the development of a number of cryogenic components which may find use in other space helium dewars, other cryogenic payloads, or cryogenic systems on Earth. These include leak-tight motor-operated cryogenic valves, cryogenic relief valves, cryogenic burst disks, gravity actuated-relief valves, liquid/vapor discriminators, a liquid/gas phase separator for normal and superfluid helium, and a large-scale, simply constructed thermomechanical pump. (See the 1991 and 1992 Research and Technology Reports for details on the SHOOT system.)

On June 21, 1993, SHOOT was launched as part of the STS-57 mission as an attached Shuttle payload (see the figure). During the first 3 days of the mission, SHOOT gathered data on the behavior of superfluid helium, particularly in the process of transferring the liquid between two 207-liter tanks. All objectives of the mission were met. Superfluid helium was transferred at various flow rates from 80 to 720 liters/hr. The astronaut crew suc-

cessfully controlled one transfer using the first expert-system software flown on the Shuttle. One dewar was warmed, then cooled to demonstrate refill of a warm dewar on orbit. Forty-one heat pulse mass gaugings were performed with accuracies ranging from 1 to 3 percent. The flow of superfluid helium was measured by two different techniques: by a *venturi* and by using the ideal performance relation of a thermomechanical pump, with an accuracy of 1 to 2 percent. The cryogenic valves and the gravity-actuated valves all performed flawlessly. Data on the performance of the two types of phase separators were gathered. Data were collected, for the first time, on the stratification of normal liquid helium in low gravity and slosh of liquid helium.

One of the primary experiments conducted by SHOOT was to investigate the performance of liquid acquisition devices (LADs) in low gravity. The LADs were different in the two dewars. The starboard dewar had a screen channel device, consisting of four rectangular cross-section arms along the wall of the tank. The port dewar LAD was made up of a number of radial vanes connected to a sponge made of Shuttle tile material that surrounded the



The SHOOT payload mounted on a Hitchhiker-M bridge in the cargo bay of Endeavour. The port and starboard dewars are in the center with the SHOOT electronics on the left and the Hitchhiker avionics on the right.

thermomechanical pump. Both LADs work by using surface tension forces to preferentially bring the liquid into proximity with the pump. We expected cavitation with the starboard LAD, since the liquid in the channel was slightly below the saturated vapor pressure. We expected the port LAD to be more susceptible to disturbing acceleration of the Shuttle. On orbit, the starboard LAD was difficult to operate, requiring a much more gradual ramping up of the flow velocity during transfer to prevent cavitation. The port LAD worked well in this regard, but the residual amount of liquid remaining in the supply dewar was somewhat greater than the starboard, 5 to 9 percent rather than 2 to 7 percent.

Among the SHOOT highlights were:

- Acquisition of the lowest temperature in orbit (<1.1 K).
- The first use of expert-system software in space.
- Mass gauging and flow metering to an accuracy of 1 to 3 percent.
- The first active management of a liquid cryogen in space.

SHOOT has successfully demonstrated the potential for superfluid helium transfer in space.

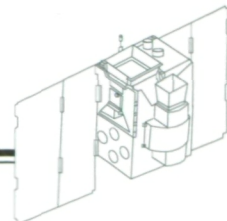
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Sponsor: Office of Space Systems Development

Dr. Michael DiPirro has worked in the Cryogenics Technology Section for the past 13 years. He has worked on the Cosmic Background Explorer (COBE), the X-ray Spectrometer for the Advanced X-ray Astrophysics Facility (AXAF/XRS), and is Principal Investigator for the SHOOT Project. He has developed a number of components for SHOOT and other cryogenic payloads.

Dr. Peter Shirron received his PhD in low-temperature physics from the University of Illinois at Urbana-Champaign in 1989. He joined the Cryogenic Technology Section of GSFC in 1989, and is Co-Investigator for the SHOOT program. He is involved in cryogenic component development for the SHOOT and AXAF/XRS projects, and in development of very sensitive low-temperature thermometry.



NASA'S FIRST IN-SPACE OPTICAL GYROSCOPE: A TECHNOLOGY EXPERIMENT ON THE X-RAY TIMING EXPLORER SPACECRAFT

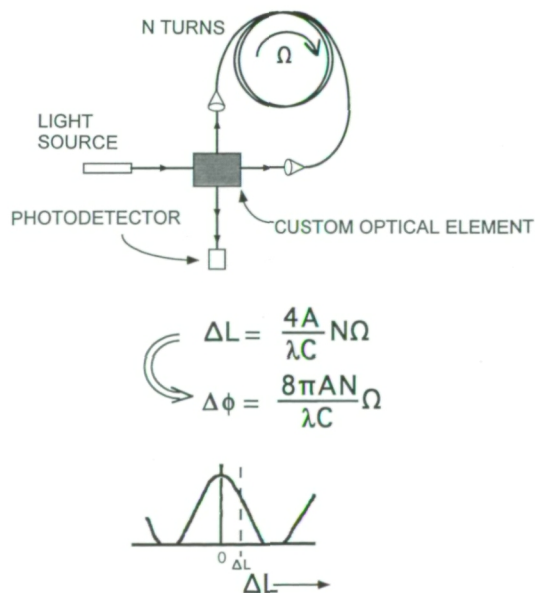
INTERFEROMETRIC Fiber-Optic Gyroscopes (IFOGs) are rotation sensors used for commercial aircraft and cruise-missile navigation. IFOGs are small, solid-state, lightweight, low-voltage and -power, alternatives to mechanical gyroscopes. IFOGs have the potential for greater than 15-year reliability, and IFOG measurement sensitivity can be improved by adjusting the fiber-loop diameter and/or the number of turns of fiber. These attributes make the IFOG an attractive candidate as a rotation sensor for low-, medium- and high-precision spacecraft attitude determination in inertial navigation systems. NASA/Goddard Space Flight Center (NASA/GSFC) and Honeywell, Inc. are teaming to fly an IFOG experiment on NASA's X-ray Timing Explorer (XTE). A closed-loop IFOG Inertial Reference Unit (IRU) will be placed on the XTE spacecraft as a separate experiment. The goal is to transfer the IFOG technology from aircraft and missile applications to routine NASA spaceflight use. This offers great benefits: NASA obtains a more cost-efficient, reliable technology for spaceflight navigation with a number of proven suppliers, and the navigation instrument market is enhanced and expanded for military/commercial suppliers.

The main objective of the XTE IFOG experiment is to prove the long-term feasibility and reliability of the IFOG technology for space navigation. Other objectives are to: (1) establish a medium-performance, space-qualified IFOG IRU standard for the NASA/GSFC Small Explorer (SMEX) Earth Probe and Discovery-class spacecraft such as XTE, Tropical Rainfall Measuring Mission (TRMM), Far-Ultraviolet Spectroscopic Explorer (FUSE), etc.; (2) provide flight heritage for a vendor-supported optical guidance-and-control component for future spacecraft; (3) increase the reliability of future NASA spacecraft to support several medium- and small-class science missions; and (4) develop low-cost, reliable, on-shore market suppliers to support NASA missions.

A Delta II is to be launched from Kennedy Space Center and carry the XTE into a 500- to 600-kilometer (km) orbit with a 28.5° inclination. The launch window is open from July 1995 to April 1996, and the mission life is to be greater than 2 years. The experiment consists of comparing the IFOG IRU attitude measurement with the XTE's primary mechanical gyroscope-based IRU attitude measurement. The primary gyroscope data are used to deter-

mine the spacecraft attitude by the XTE on-board computer and GSFC ground-based computers. In contrast, the IFOG IRU data will be processed solely by the ground-based computers for determination of the XTE attitude. This measurement comparison will be routinely conducted over the XTE 2-year mission life.

The XTE satellite IFOG IRU experiment utilizes three IFOG sensors mounted at right angles to one another on a sensor block assembly. The IFOG consists of an infrared, solid-state light source coupled to an optical fiber, a custom optical element, 1 km of optical fiber wound on a 3-inch coil, a photodetector, and signal processing electronics, as shown in the figure. The custom optical element specially prepares and then splits the source light into two beams of equal intensity. The two beams traverse the fiber-optic coil, one clockwise and the other, counter-clockwise. They then recombine at the element and produce an interference pattern at the photodetector, shown in the bottom part of the figure. In the absence of rotation, the clockwise and counter-clockwise beams travel identical path lengths inside the sensing coil. In the presence of rotation, the two beams experience a path length difference, ΔL , that results in a phase shift, $\Delta\phi$, in the detected



Interference Fringe Pattern at the Photodetector.

interference pattern. Notice that the path length difference is dependent on the area, A , wavelength, λ , speed of light, C , number of fiber turns on the coil, N , and sensor rotation rate, Ω .

Dr. Glenn Sanders from Honeywell, Phoenix, Arizona, provided outstanding technical contributions to the IFOG technology, and William Taylor from Honeywell, Clearwater, Florida, provided the technical leadership that will enable the IFOG IRU to be flown on the XTE.

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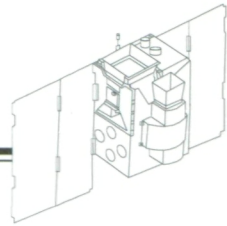
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Sponsor: Office of Safety and Mission Assurance

Mr. Glenn Unger is the IFOG Experiment Manager and Co-PI on the XTE mission. He earned his Master's in Electrical Engineering from the Johns Hopkins University in 1985. Mr. Unger has been at GSFC for 11 years, where he is a member of the technical staff in the Photonics Branch.

Mr. David Kaufman is an IFOG experiment Integration and Test engineer on the XTE mission. Mr. Kaufman earned his Bachelor's in Electrical Engineering from the Rensselaer Polytechnic Institute. Mr. Kaufman has been at GSFC for over 3 years, where he is a member of the technical staff in the Photonics Branch.

Dr. Michael Krainak is Head of the Opto-electronics Section and an IFOG Co-PI. He earned his PhD in Electrical Engineering from the Johns Hopkins University. He has worked for AT&T, the National Security Agency, and, for the past 3 years, at GSFC.

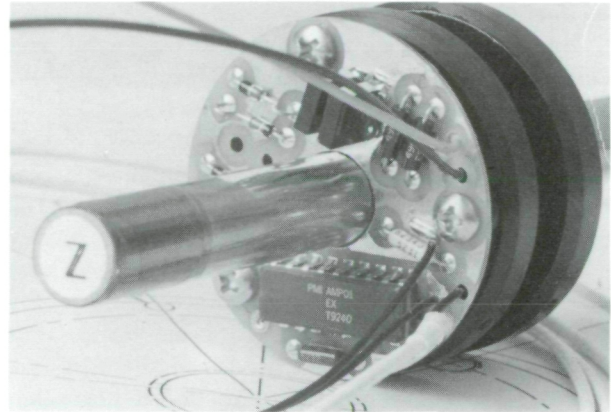


A NEW LIGHTWEIGHT SEARCH COIL FOR SPACE

A SEARCH COIL is a device that measures fluctuating magnetic fields. It consists of a magnetic antenna and associated electronics. When used on sounding rockets or on spacecraft, search coils are usually boom-mounted in order to escape the electromagnetic noise within and near the spacecraft body generated by other scientific instruments and spacecraft subsystems. As a general rule, scientific instrumentation should impact mass constraints as little as possible, but boom-mounted instruments in particular must be lightweight to survive deployment under high stress conditions. This weight constraint can limit both the size of the sensor and its placement on the boom. Both factors translate into severe constraints on the capability of the instrument to measure the weak electromagnetic fields often encountered in space. To address these limitations, NASA scientists and engineers in the Planetary Magnetospheres Branch have developed a magnetic search-coil antenna system whose sensing element is 83 percent less massive than previous designs (see the figure).

The new, lightweight design is achieved through the use of a new sensor material, *metglas*. Although the new material is twice as dense as the previously used ferrimagnetic (ferrite) material, the same design criteria are met with only 7 percent as much material. Because of its pliability, *metglas* can conform to almost any desired shape. Key properties of the ferrite material, such as its low ohmic loss and high magnetic permeability, are also found in *metglas*. Structural integrity of the new material is limited only by the substrate upon which it is fastened.

The newly designed search coils have been and are being flown on sounding rockets in order to test the new system's performance in flight. A single-axis version of a prototype search coil was launched on a Black Brant as part of an extensive scientific package to investigate intense sporadic E-layers in the Earth's ionosphere. A full-up, 3-axis system is scheduled to be launched as part of a sounding rocket program to study the generation mechanisms re-



Tri-axial metglas search coil being readied for sounding rocket launch into pulsating aurora.

sponsible for Earth's pulsating aurorae.

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Sponsor: Office of Space Science

Dr. William Farrell is a co-investigator of GGS Wind/MFI and Cassini/RPWS. He earned a PhD in Physics at the University of Iowa in 1987. His professional interests include analysis of radio- and plasma-wave data, data compression, and receiver design.

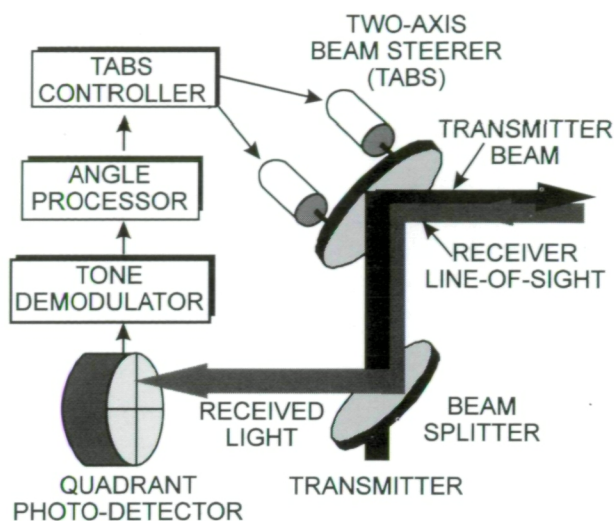
Dr. Michael Desch is a co-investigator on the planetary radio astronomy experiment on Voyagers 1 and 2, and the radio- and plasma-wave instrument on Ulysses. He has a PhD in Astronomy from the University of Florida. He specializes in the analysis of spacecraft observations of magnetospheric phenomena.

FREE-SPACE LASER COMMUNICATION POINTING AND TRACKING

NASA's 1992 STRATEGIC PLAN mandates a quantum leap in data throughput for spacecraft and communication and data systems. Operationally, this means the existing Tracking and Data Relay Satellite System (TDRSS) capacity of 300 megabits per second (Mbps) must be raised into the gigabit-per-second range. The new TDRSS II (RFP pending) is expected to include both an increased data capacity and a data crosslink between the TDRS in view of the White Sands Ground Terminal and the TDRS over the Indian Ocean which is out of view of the White Sands Ground Terminal. As currently defined, this crosslink is to carry 650 Mbps and span 123° of orbital arc (approximately 80,000 km), and is in addition to the existing space-to-space links provided by TDRSS.

Microwave communications crosslink systems that would support this high data rate and long range will have antenna apertures that reach 4.9 meters in diameter and have subsystem weights in excess of 180 kg. Laser crosslink systems have advantages that address these issues. Laser crosslink systems of equal performance will have antenna apertures (optical telescopes) of less than 0.36 meter and correspondingly less system weight, entirely due to the much higher carrier frequency (10^{15} Hertz (Hz) vs. 10^{10} Hz). The laser spectrum is also much less congested than the microwave spectrum, providing much greater freedom from interference and from restricted spectrum allocation.

A key subsystem in a laser communications terminal is the Pointing, Acquisition and Tracking Subsystem (PATs) which must quickly acquire and accurately track the cooperating laser terminal with which it is communicating. Lasers naturally have small beam divergence angles (on the order of 10 microradians (2 arcseconds)). This is the angle a dime subtends at 1.8 km; even over an 80,000-km crosslink, the beam will only be 800 meters in diameter. To keep this narrow beam on a target 80,000 km away requires a tracking system that is accurate to less than a microradian in a base-motion disturbance environment that extends up to several hundred Hz. The key subsystem component for achieving this is the fine-steering servo loop. The first figure illustrates the major elements of this servo loop. The most critical and state-of-the-art component is the electromechanical two-axis beam steerer (TABS) mirror assembly, which is a two-

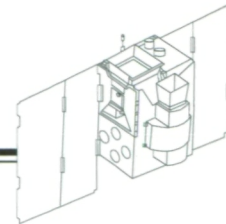


Fine-steering servo loop.

axis gimballed flat mirror with integral drivers and rate feedback.

The TABS mirror must have low mass so that high-frequency motion compensation is possible. It must also be compact and reliable because it must fit within a highly integrated optics assembly without excess room or mass allowance for a bulky or redundant mechanism. TABS was designed and fabricated by General Scanning, Inc. to our specifications; it is internally fully redundant and is made with a lightweight beryllium mirror that is dynamically balanced about both axes of motion. It weighs 240 grams and requires less than 2 watts of power. The TABS servo subsystem performance requirements are derived from the requirements expected for the TDRS II mission. It was designed, built and tested to these expected requirements in our labs.

The major components in this servo loop, as illustrated in the first figure, are TABS, the quadrant photodiode detector, the track beacon demodulator, the angle processor, and the TABS controller. The beam splitter shown in the figure is not functionally part of the servo loop, but is needed for full duplex transmitter and receiver operation. This splitter separates the transmitted and received beams so that a single TABS can be used for simultaneously steering both of these beams in a common optical path.

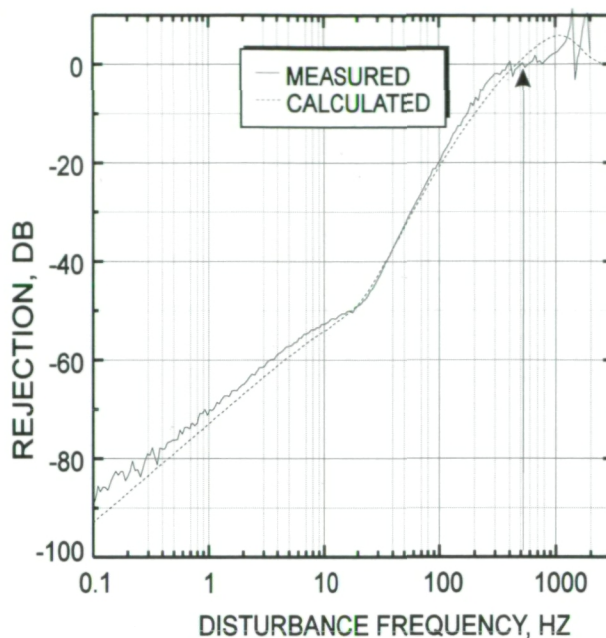


The quadrant photodiode detector is a 2 x 2 array of photodiodes whose output signals are in proportion to the relative amount of received laser energy being imaged onto each quadrant. This output is processed by the rest of the circuitry to generate the angular pointing error. The track beacon demodulator locks onto and then removes the terminal-unique tone modulation placed onto the track beacon laser by the transmitting terminal. This allows the tracking (receiving) terminal to discriminate against other terminals, stars, and other bright objects in the field of view; to avoid self-jamming; and to move the demodulated spectrum beyond the $1/f$ noise inherent in all electronics.

The angle processor is one of two types we have developed. This circuit processes the four demodulated quadrant signals into two orthogonal line-of-sight error signals for input into the TABS controller. The controller takes these error signals and adjusts the electrical currents to the TABS actuators so that these error signals are attenuated. The design for the controller implements proportional-integral feedback with a series lead network providing the necessary phase and amplitude stability for the servo loop.

The two angle processors we developed provide two different functions. The first is a linear ratiometric processor which is extremely accurate over a small range of angles near the center of the field of view; the second is a digital "bang-bang" processor that is very simple, compact, and has a wide dynamic range making it more suitable for correcting angle errors over the entire field of view, such as during terminal acquisition. Both were built and tested, but since the linear processor is the more critical for fine-precision tracking, the analysis and test results for it will only be presented.

The ultimate performance requirement is the servo system's ability to reject or compensate base motion disturbances. After the circuits were designed, built, and integrated into the TABS, an optical test bench was assembled so that base-motion disturbance rejection could be measured. This test setup used a very high-speed piezoelectric mirror to disturb the incoming test laser beam in such a way that it simulated the expected base-motion disturbance environment expected on a TDRS II satellite. This input was focused onto the quadrant detector via a reflection from TABS as shown in the first figure (but without the beam splitter). The rejection measure is the angle processor output error signal divided by the piezo-



Base-motion-disturbance rejection.

electric mirror input disturbance. This ratio was continuously measured and computed while the piezo device swept through a frequency range of 0.1 to 2,000 Hz.

The disturbance rejection test and analytical results are given in the second figure. From this plot, it can be seen that at 0.1 Hz there is ~90 decibels (dB) of rejections (i.e., any base-motion disturbance at this frequency will be reduced by 9 orders of magnitude (10^{-9})). At 10 Hz there is over 50 dB, or 5 orders of magnitude reduction; at 400 Hz the rejection approaches 0 dB, and no attenuation occurs to base motion disturbances above this frequency. We found close agreement between analytical (calculated) and test results.

For postulated and measured spacecraft disturbances, the performance of our fine-steering servo loop is adequate to provide an overall pointing error of less than 1 microradian. Consequently, we have shown that this performance requirement, which is of great concern to the laser communications systems designers, can be adequately dealt with without sacrificing size, weight, power, or simplicity.

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ENGINEERING AND MATERIALS

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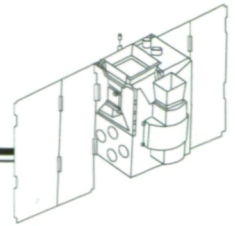
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Sponsor: Office of Space Research

Mr. William Hayden is an electro-optical systems analyst and lead pointing and tracking engineer on GSFC's optical communication program. He received a Master's in Electrical Engineering from the University of Missouri at Rolla, and has been working at GSFC for 4 years, after having spent 10 years in industry.

Ms. Toni McCullough is an electro-mechanical engineer designing mechanisms and control circuits for numerous flight projects. She received a Bachelor's in Electrical Engineering from West Virginia University, and has been at GSFC for 4 years.

Mr. Alan Reph is a controls systems engineer performing attitude-control analyses on both the TOMS and TRMM flight projects in the Guidance and Control Branch. He received a Master's in Electrical Engineering from The Johns Hopkins University, and has been working at GSFC for 4 years.



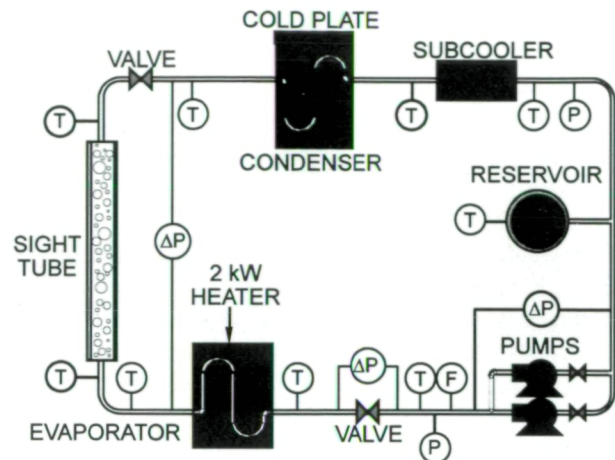
FLOW VISUALIZATION OF TWO-PHASE R-134A IN A VERTICAL TUBE

WITH THE INCREASE in power requirements of today's spacecraft, improved thermal-control systems are necessary to dissipate excess heat. Earlier methods of heat removal utilized single-component, active thermal control systems, which store the heat energy in the sensible energy of the working fluid. The sensible energy is manifested as the temperature rise of a fluid when heat is added. Current technology is pursuing two-phase systems which store excess heat energy in the latent heat of vaporization, which is responsible for the phase change of material from liquid to gas. The inherent advantages of a two-phase system are the constant temperature at which the system is maintained, better temperature control, and the increased thermal capacitance offered by the latent heat.

This experiment was designed to investigate the behavior of two-phase flow in a vertical tube. Specifically, it seeks to correlate the relationships between flow regimes, fluid quality, pressure drop, and flow rate. The flow regime is a visual datum which characterizes the geometry of the gas phase within flow. These geometries vary from pure liquid flow, to bubbly flow (small discrete bubbles), to slug flow (large conjoined bubbles which are the shape of bullets), to churn flow (a turbulent mixture of the liquid and vapor phases), to annular flow (a distinct column of gas which passes through the center of the tube), and finally to pure vapor flow.

Previous two-phase flow research focused on mixtures of gas and liquid as the working fluids. However, results from the studies of gas-liquid mixtures do not apply to the design of thermal control loops which employ single-component fluids. Since it is the utilization of the heat of vaporization and their isothermality that make two-phase systems optimal for thermal control, the interest in flow regime characterization is limited to two-phase fluids consisting of only liquid and vapor phases of a single component.

A two-phase loop with the refrigerant R-134a as the working fluid was used to measure specific flow parameters, demonstrate flow visualization techniques, and establish system dynamics. As shown in the figure, the loop consisted of two gear pumps (low and high flow rates), three differential pressure transducers (ΔP), two absolute pressure transducers (P), an evaporator with 2 kW of heater



Experiment diagram for two-phase flow visualization.

power, a condenser, a subcooler, a flow meter (F), a reservoir with temperature controller, various thermocouples (T), and a vertical sight tube. The data were collected using a signal conditioning box and an analog-to-digital converter board in a personal computer. The various flow regimes were recorded through the sight tube using a video camera with a special macro lens and high-resolution 8-mm video film.

The vertical orientation of the sight tube was used to minimize the effect of gravity, since stratified flow is common in ground-based two-phase flow, but is uncharacteristic in a microgravity environment. In addition to the flow-regime characterization, the effect of quality on pressure drops throughout the system was studied. Pressure drop considerations play a major role in the design of two-phase thermal systems.

To begin testing, the saturation temperature of 27 °C is set by heaters and a temperature controller on the reservoir. The system is brought to thermal equilibrium by running the pump for 5 minutes before heat is added in the evaporator. Since the system is at an equilibrium at the saturated liquid state, any additional heat which is added should begin to vaporize the liquid to a set quality.

The testing was done under two types of conditions: constant flow rate with varying heat input to the evaporator and constant heat input with varying flow rate. The first

two runs were done with constant flow rates of 54 and 73 g/min, and the heat inputs varied from 0 to 200 W and 0 to 300 W, respectively. There were four points to note about the results from both runs: (1) the outlet from the evaporator would reach several degrees above saturation, known as superheating, just prior to the onset of vaporization and then drop to saturation once vaporization started; (2) the predominant flow regime was churn, with occasional slug flow; (3) once total vaporization, referred to as dry-out, had occurred, the temperature of the evaporator would rise rapidly; and (4) the pressure drop across the sight tube and valve would change from about 0 kPa during pure liquid flow, to about 6.9 kPa during mixed flow, and then to about 1.4 kPa at complete vaporization. For (1), the superheat in this system is characteristic of most pumped loops and is probably due to the use of smooth drawn tubing and glass, which limits the number of nucleation sites at which vaporization would occur. This superheating would also cause vaporization to begin with churn flow instead of the normal bubbly flow. If the heat input is lowered below the point at which vaporization occurs, the gaseous phase becomes more well-behaved, and the bubbles form slugs. The slugs are interspersed with smaller bubbles which join with slugs as they rise along the vertical tube due to the decrease in head pressure. As expected, the loop remains at a constant temperature for any power setting that maintains a two-phase working fluid. At higher heat settings, the flow returns to churn flow and increases in its turbulence until dry-out occurs. After dry-out, the heat transfer coefficient of the pure gas coefficient is so poor that the temperature of the evaporator plate rises dramatically, since the working fluid is no longer serving as an adequate heat sink.

The second type of testing undertaken was at constant power and variable flow rate. The power to the evaporator was set at 150 W, and the flow rate increased from 16 g/min to about 200 g/min and then decreased to a low flow rate. The system once again exhibited superheating characteristics before vaporization. The system proceeded from a churn flow at low flow rates to a slug flow at high

flow rates, and finally recondensed to a single phase. The results for the pressure drops were the same as those found in the previous runs. The test was repeated using 300 W with similar results.

Other test runs showed that a bubbly flow can be produced at high flow rates and moderate power settings. A form of wavy annular flow has been produced at high flow rates, and high power settings. Knowing that these two conditions can be produced, all two-phase phenomena can now be investigated.

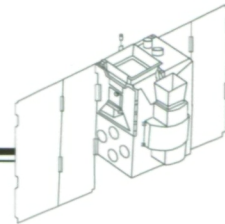
The results of this study will be used to design a flight experiment and define a mission scenario for a flight experiment to collect data on two-phase behavior in microgravity. The ground-based test data from experiments like this one will serve as a baseline for comparison to flight results so that gravity-specific parameters can be identified and included in the analytical development. Ultimately, the ground-based and microgravity data will be used to improve correlations and analytical models based on fundamental principles. This information and the resulting "validated" models can then be used to improve the design of spacecraft thermal control systems, propulsion systems, and other fluid-based systems used in a space environment.

This work was performed in collaboration with Robert L. Bayt and Kimberly R. Kolos, graduate students at Purdue University and the University of Maryland, respectively, under the expert guidance and supervision of Gerard W. Durback (Code 741).

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Sponsor: GSFC Director's Discretionary Fund

Dr. Steve Benner has been at GSFC for 5 years working in the Thermal Engineering Branch on two-phase thermal systems. Dr. Benner earned a PhD in Chemical Engineering at Ohio State University.



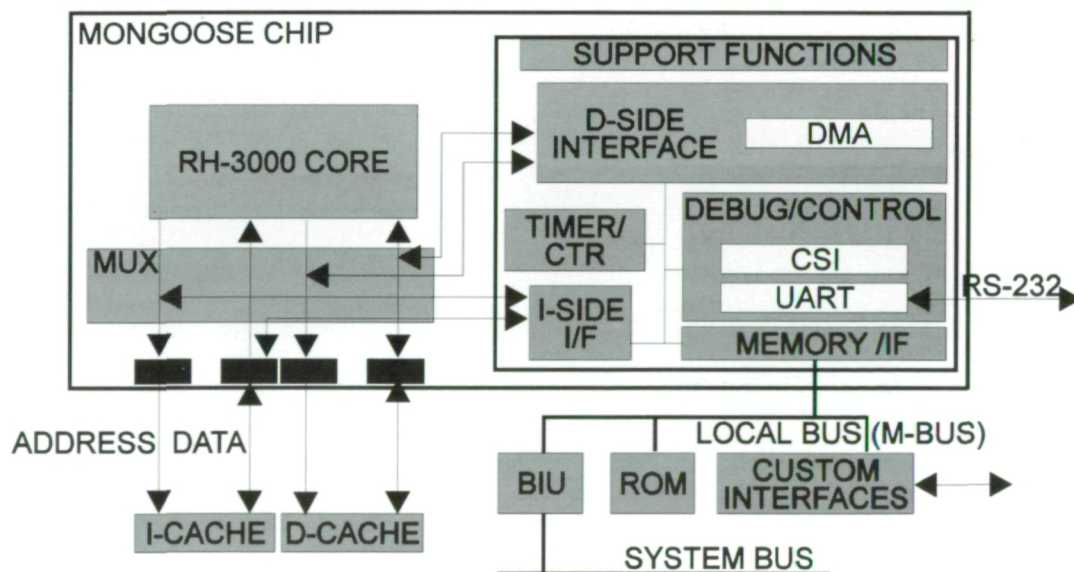
MONGOOSE MICROPROCESSOR

AS SPACECRAFT FUNCTIONS become more complex, and decision-making is relegated to on-board capabilities, increasingly capable microprocessors must be used. Commercial microprocessors have grown enormously in capability and in transistor count, while the chip size remains essentially the same. The very design practices which facilitate this speed and density cause the integrated circuits to be susceptible to the effects of cosmic energetic particles. These effects manifest themselves in the form of single-event phenomena: upsets or latchup caused by the deposition of charge as the particle passes through the circuit. Previous techniques for advanced flight computers using state-of-the-art components included many layers of redundancy in hardware, software, and operations. Spare units, multiple execution, and "watch dog" timers have been used.

The Mongoose microprocessor, a MIPS R3000-compatible microprocessor developed by the Electrical Engineering Division, approaches this problem differently. Mongoose consists of a processor core, selected peripherals, and input/output capabilities. These functions have been integrated into a single, radiation-hardened application-specific integrated circuit (ASIC). Mongoose retains the basic functionality of the R3000 architecture, with added features consistent with spacecraft applications. The functions are divided, as shown in the figure. The major

functions are divided into three sections: the R3000 core, the cache interfaces, and support functions. The R3000 core was modified to radiation-hard design rules, but otherwise left intact. The cache interface section handles all core accesses to the data and instruction memory. The support function block includes several sub-blocks:

- The D-side interface—handles all core accesses to data on the general-purpose bus (M-Bus);
- The I-side interface—handles instruction fetches from the uncached memory section (M-Bus);
- The DMA channel—a single-channel direct memory access controller for block moves of data between D-Cache and M-Bus, or M-Bus and M-Bus;
- The Timer-Counter Block—two 32-bit timers, one dedicated for use as a system watchdog, and the other one as general purpose. Both provide interrupts to the core upon timeout;
- The Debug/Control Block—contains an Intel i8251-compatible communication channel for code loads, monitoring, and in-flight use. The Command/Status Interface (CSI) is also contained within the Debug/Control Block. This section provides control and status registers for all of the Mongoose Support Functions;



Mongoose Processor Architecture.

- The Memory Interface—this block is predominantly a state machine controller for the M-Bus interface. It handles all transactions on the M-Bus, including the generation of wait-states and termination of transactions due to errors.

Mongoose was manufactured using LSI Logic's LRH20K Gate Array process. This process is designed for military-level radiation tolerance, and, as such, provides protection against cosmic radiation as well. Its parameters are guaranteed to a total dose level of 3 MRads. Single-event upset susceptibility has been tested at DOE's Brookhaven National Laboratory; Mongoose shows an error rate of one error per 100 years in a worst-case Earth orbit.

The availability of commercial software-development tools from many vendors was a major factor in the decision to base Mongoose on the R3000. The Mongoose architecture follows the R3000 exactly to allow the use of these tools. Compilers, debuggers, and libraries are available to run on PCs and workstations from IBM, MIPS, Sun, DEC, and others. A programmable, read-only memory monitor/debugger has been ported from the Free

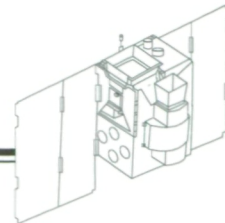
Software Foundation's PMON to Mongoose. This program, PMONGoose, allows the setting and monitoring of breakpoints, register control, and provides a means of downloading code into the processor's random-access memory.

The Mongoose ASIC is being used in the XTE, slated for launch in 1995, as an instrument telemetry interface controller, and in the Tropical Rainfall Measuring Mission, slated for launch in 1996, as part of a power subsystem controller.

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Sponsor: Office of Space Science

Mr. Brian Smith is a computer design engineer in the Flight Data Systems Branch. He earned a Bachelor of Engineering in Electrical Engineering from the State University of New York, Maritime College, and a Master of Engineering, Electrical, from Stevens Institute of Technology. Mr. Smith has been at GSFC for 4 years developing data systems.



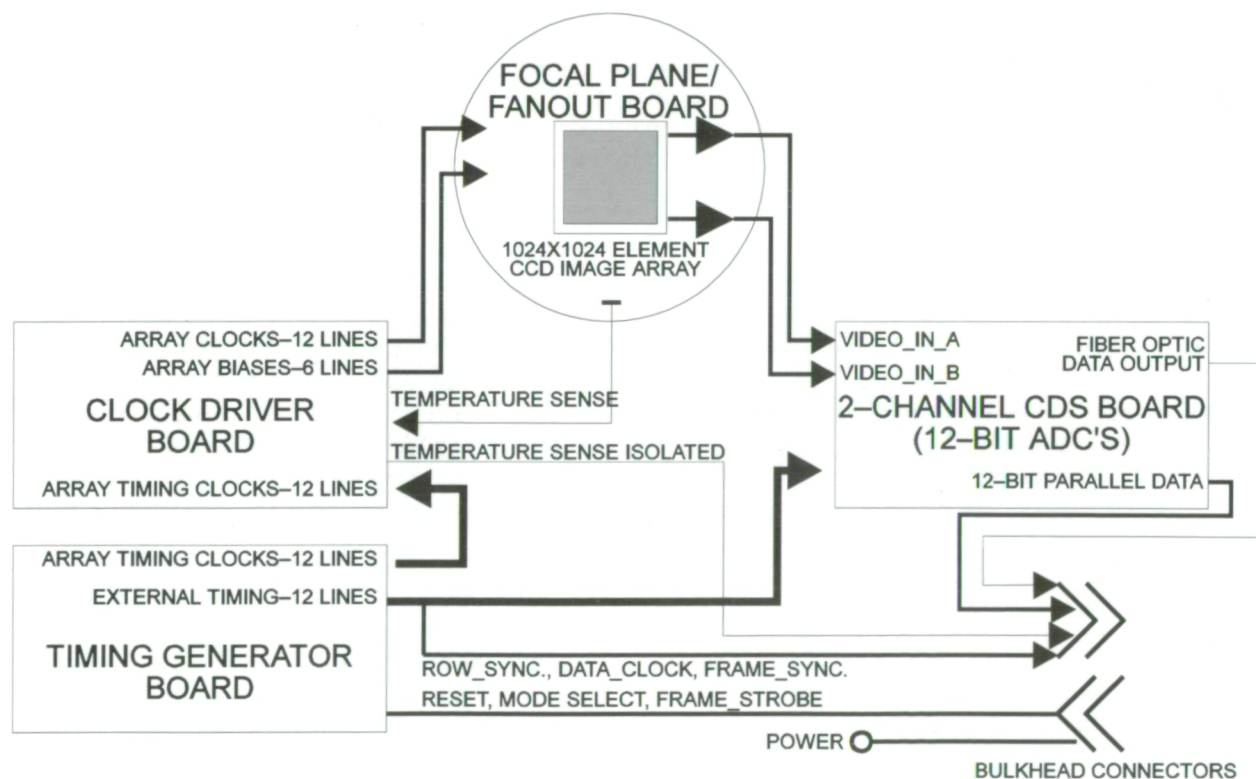
GENERAL-PURPOSE/FLEXIBLE FOCAL PLANE ELECTRONICS AND DATA ACQUISITION SYSTEM

A FLEXIBLE SET of charge-coupled device (CCD)/charge-injection device (CID) image array support boards and data systems has been developed recently by Codes 920 and 710. These electronics were originally developed to upgrade the Advanced Solid-State Array Spectroradiometer (ASAS). The upgraded ASAS was successfully deployed on the NASA/ARC C-130 to Niger, W. Africa, in support of the HAPEX-II/SAHEL field experiment. The new CCD detector array and its associated electronics greatly improved the utility of the ASAS instrument for HAPEX, and for a recent Landsat-7 simulation mission.

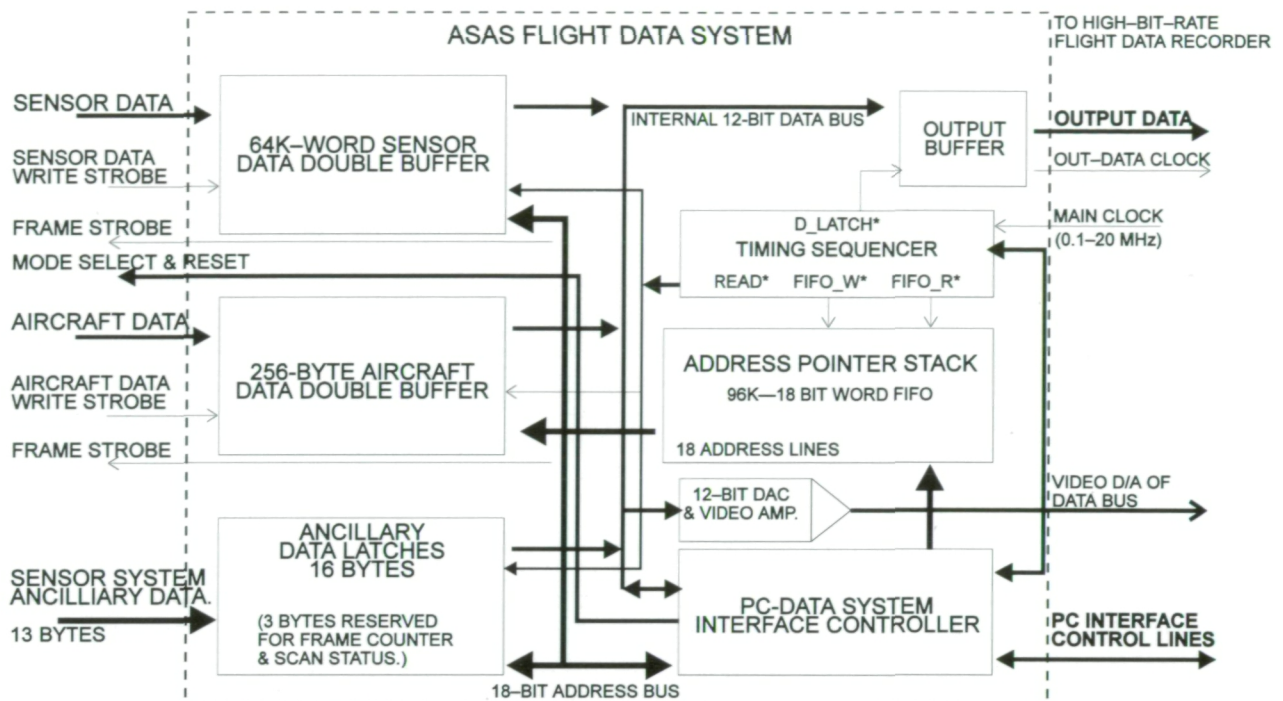
The array boards consist of four boards, each performing specific functions which may be reconfigured when necessary, depending on the application: an electronically programmable and externally controllable timing generator board; a clock driver board; a correlated double-sam-

pling analog-to-digital conversion (ADC) board; and a focal plane/fan-out board. Additionally, a data system board was developed which allows 12-bit asynchronous sensor and aircraft ancillary data to be acquired and streamed to either a synchronous 14-track flight data recorder or a buffered asynchronous serial or parallel flight data recorder. The format of the data stream is user-definable at start-up, and can provide data blocks ranging from 16,000 to 96,000 words. Utilizing these flexible components, a variety of CCD/CID array-based sensors may be built with minimal expenditure of development time and cost.

The first figure shows a block diagram of the focal plane support boards and the basic interconnections between them. The second figure shows the functional block diagram of the Synchronous Output Flight Data System (SOFDS). The control signal labels and block names are



ASAS Focal-Plane Electronics Block Diagram.



ASAS Flight Data System.

those used for the ASAS, specifically. The variable hardware components in this diagram are the driver board and the focal plane/fan-out board. Changing detector arrays changes the required number and voltages of clocks and bias voltages. A different detector array will usually require a different fan-out board, since the package size and pin definitions are unique.

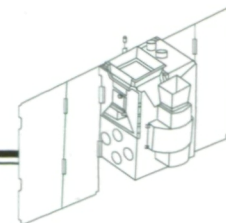
The timing generator utilizes an electronically programmable sequencer/controller to monitor four external control signals from the data system, and to generate 24 individual timing signals: 12 that can be used to drive optically isolated array drivers and 12 others for external logic timing. Array clock signals travel through a header connector to opto-isolators on the driver board, where they are buffered and level-shifted to the required clock voltages. From the driver board, the array clock signals and the bias voltages that are generated on the driver board travel on low-noise coaxial cables to the focal plane/fan-out board where they drive the image array.

The array output signal is buffered on the focal plane/fan-out board and sent to the Correlated Double Sampling (CDS) ADC board. The CDS board digitizes both the reset level and video level to eliminate variations in the re-

set level as a noise source. The CDS Board digital data can be transmitted via parallel differential transistor-transistor logic (TTL) outputs and/or 17-Mbps serial fiber-optic output to the SOFDS or any data system that has the necessary receiver components.

The SOFDS double-buffers the image and external ancillary data, and retransmits the data in a continuous synchronous stream to an Ampex AHBR-1700i flight-data tape recorder at 1.5 MegaWords/second (2.2 Mbps). A continuous stream of data is necessary since the recorder does not buffer the data and, therefore, must run continuously. The SOFDS has an estimated maximum output data rate of 3 MegaWords/sec (4.5 Mbps). The contents of the data bus are also converted to an analog signal for display on an oscilloscope to allow immediate verification of system operation.

The SOFDS output data block is user-definable and is loaded from an ASCII "Address Pointer Stack" file via a PC-SOFDS interface after power-up. This feature increases efficiency by enabling the selection of only relevant data in the most efficient order for post-processing. This random access is accomplished by providing a hardware address for each data element and using a self-cycling address pointer stack memory.



A new array driver board was developed to drive a Virtual-Phase CCD Array (VPCCDA) from TI-Japan. The TI-Japan array will be utilized for several instrument focal planes, including a hand-held, portable, bidirectional reflectance camera being developed with funding from the GSFC Director's Discretionary Fund. Although this array requires fewer clock lines, they are bipolar; as a result, the driver board built for the ASAS Thomson CCD array cannot be used, as the ASAS clocks are all positive unipolar voltages. The TI-Japan focal-plane support boards will utilize the fan-out board that was developed for use with the Code 718 detector test-bed. The fan-out board usually mounts inside a specialized Lakeshore Dewar for temperature and humidity control during testing. Using the existing board will further reduce the development costs associated with the TI-Japan VPCCDA.

The Ampex flight recorder used with the present flight data system is being replaced by a buffered very large data storage (VLDS) flight recorder from Metrum, Inc. This recorder will record asynchronous data at average data rates of up to 4 Mbps with a total capacity of 10.6 gigabytes on a T-120 SVHS videocassette.

We plan to complete this system with a more general-purpose driver board which can drive any of the imaging arrays on the market with a change of resistors to set the bias and clock voltage levels. We also plan to develop a Thermo-Electrically Cooled (TEC) fan-out board interface to allow direct use of the fan-out boards used during the initial array test phase and provide operating temperature control, and a redesigned data system card with a 16-bit data bus, high-speed fiber-optic-coupled data input/output, and Programmable Logic Devices (PLD) to reduce the parts count and power consumption while increasing flexibility. Given the interest in solid-state detector arrays, these innovations have great potential for technology transfer.

We would like to recognize the efforts of David Graham (Hughes-STX), William Kovalick (Hughes-STX), Ravi

Kaipa (Hughes-STX), Marilyn Hostetter (718.2), Peter Shu (718), and Roy Johnson (718.2), whose dedication has contributed to the successful development of these systems.

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Sponsor: GSFC Director's Discretionary Fund

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Mr. Jeffrey Travis holds a BS in Electrical Engineering from the University of Michigan. He has served 6 years in the Space Sciences and Engineering Directorates at GSFC, and currently heads the Detector Systems Section.

Mr. Michael Kasten is supporting the Composite Infrared Spectrometer (CIRS), the BRSR, and the ASAS as a digital design engineer. He is responsible for the design of the CIRS front-end electronics and the ASAS CDS electronics using Field Programmable Gate Arrays (FPGAs) and high-speed fiber-optic data I/O. Mr. Kasten earned a BS in Computer Engineering from Virginia Tech. For the past 3 years, he has been involved in the design and test of electronic subsystems for ASAS and CIRS and a fiber-optic-coupled programmable voltage controller at GSFC.

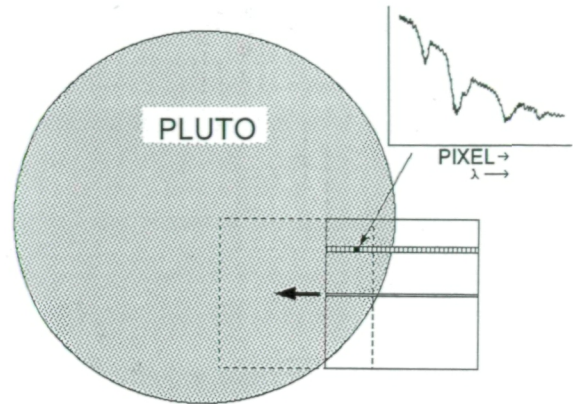
AN INFRARED MAPPING SPECTROMETER FOR THE PLUTO FAST FLYBY MISSION

THE PLUTO FAST FLYBY (PFF) is a low-cost mission planned for launch in 1999 and arrival at the Pluto-Charon system in 2006. Two spacecraft will encounter Pluto and its moon Charon, with arrivals separated by 180 to 400 days. The challenge of the PFF Mission is to build instruments with low mass and power requirements, and which make optimum use of data storage while accomplishing the mission goals. The mass of each spacecraft will be less than 150 kg. The strawman payload includes an ultraviolet spectrometer, a visible imager, a radio science experiment, and an infrared spectral imager.

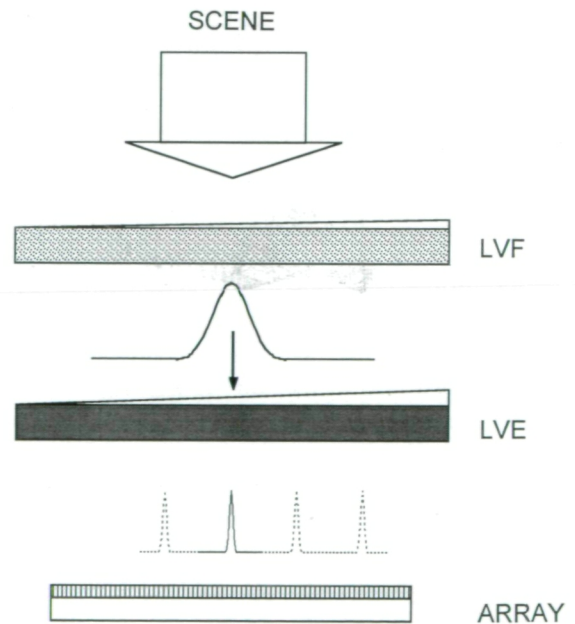
The Linear Etalon Imaging Spectral Array (LEISA) infrared mapping spectrometer being developed for the PFF Mission meets this challenge with a simple optical design, minimum electronics, and by using the spacecraft command and data handling (C&DH) system for scientific data handling, as well. Costs and risks are kept low with proven technology. LEISA will meet the mass, power, and science requirements of the PFF mission, and can be constructed within the state of the art.

The requirements for an infrared imaging spectrometer for the PFF mission are ideally matched with the capabilities of LEISA, a new concept in infrared imaging array spectrometers. The spectral coverage, resolving power, field of view, and sensitivity needed at Pluto and Charon are achievable with an extremely simple focal plane consisting of only a detector array placed behind a linear-variable etalon (LVE). This spectrometer has no moving parts, a minimum of optical elements, and only one electronically activated component, the array itself. Compared to conventional grating (prism) spectrometers or tunable filter systems, it represents a significant reduction in opto-mechanical complexity. LEISA creates a spectrum in one dimension of the Near Infrared Camera and Multi-object Spectrometer (NICMOS) detector array, while the scene is imaged in both dimensions. NICMOS was developed for the Hubble Space Telescope (HST). The instrument is designed to cover the 1.0- to 2.5- μm wavelength range with a spectral resolving power ($\lambda/\Delta\lambda$) of 300 and a spatial resolution of 53 microradians. A full spectrum at each position in the field of view will be obtained by turning the spacecraft in the plane along the spectral dimension, so that all points are swept through all wavelengths (see the first figure). The key to this spectrometer is the LVE, a wedged dielectric etalon whose spectral passband varies with position (see the second figure). Each

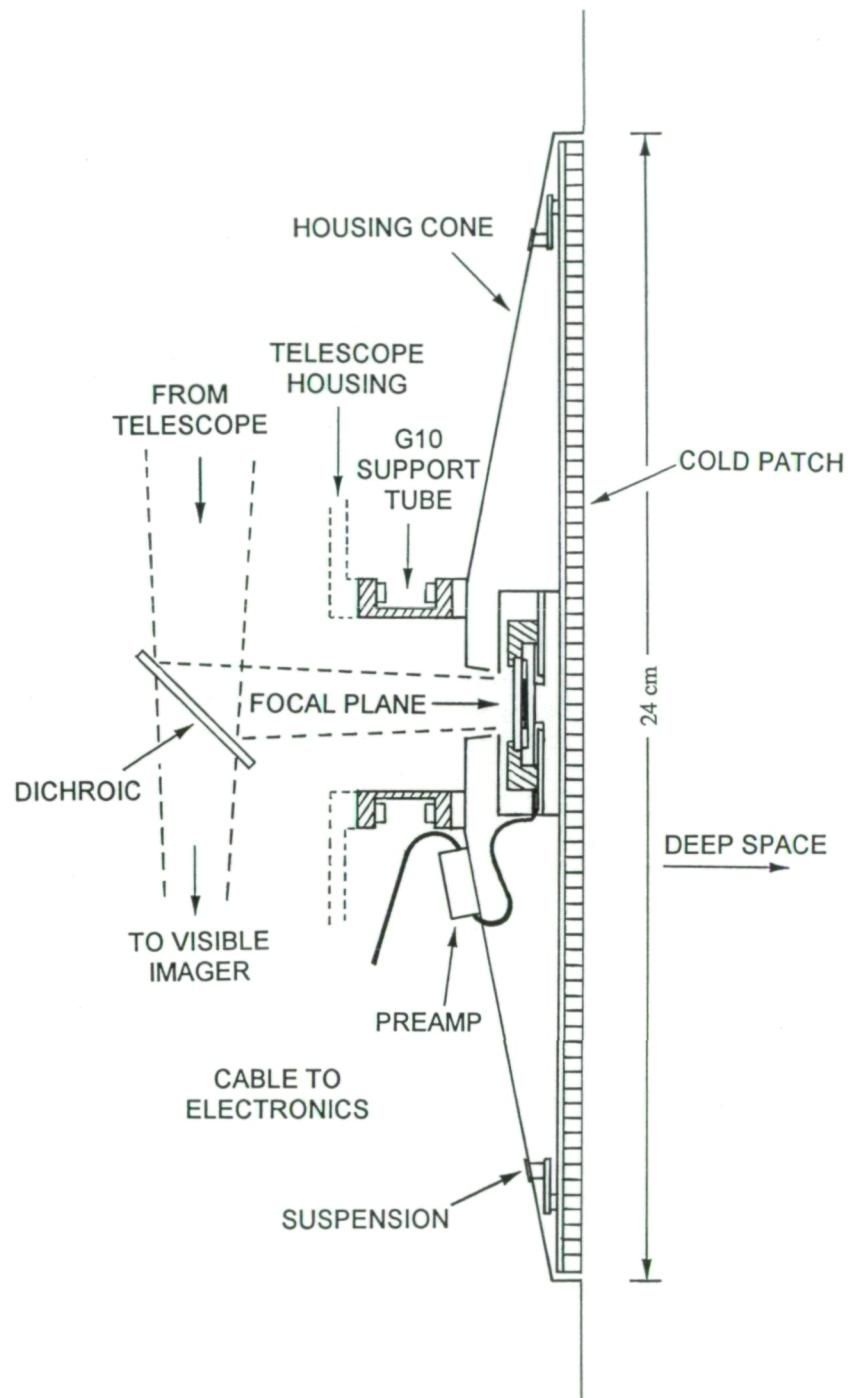
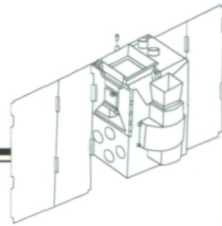
column of pixels, therefore, sees a different wavelength, and a spectrum is formed in each row. The LVE is used in com-



LEISA will operate by imaging Pluto in two dimensions on the array. As each spatial point is scanned along one row of the array by moving the spacecraft, the spectrum of that point is recorded.



At each position along its surface, the LVE has many transmission fringes spaced in wavelength. One of these is selected by the LVF and passed to the detector array. The LVE is wedged, so that the transmitted wavelength varies along the array.



The detector array and filter assembly are mounted on a radiative cooler. The telescope is shared with a visible camera. A dichroic filter in the telescope splits incoming beams into infrared and visible components; the infrared is focused through the LVE/LVF onto the array.

bination with a lower resolution linear-variable filter (LVF) which order-sorts the etalon. The recent development of miniature LVEs and LVFs makes possible the construction of this spectrometer. The LVE/LVF assembly is placed over the array to form the imaging spectrometer. The 256x256 NICMOS arrays now available are well-suited for use with the LVE, which makes this approach practical for imaging.

The detector array must be operated at a temperature of 90 to 95 Kelvin (K). To achieve this, the LVE/LVF assembly and array will be mounted on a radiative cooler. The cooler works by exposing a black-painted surface to cold space. The spectrometer and cooler have no moving parts.

The electronics are designed to require minimum power and number of components. The NICMOS array is clocked at a bit rate close to the serial I/O rate and is designed to run in only one mode, so that no CPU, memory, or external multiplexer is required. Clocking, A/D control, and parallel-to-serial conversion is provided by a field-programmable gate array. All data processing is done by the spacecraft C&DH system. By minimizing the requirements placed on the clocking and signal electronics in this way, the mass and power requirements are minimized as well.

LEISA will share a telescope with the visible camera on the spacecraft (see the third figure). The telescope will have a 75-mm aperture and a 750-mm focal length. LEISA will mount at an interface flange on the side of the telescope, and receive the infrared beam from a dichroic filter which separates the light into visible and infrared components. A small, off-axis mirror will be placed near the edge of the telescope objective for observing Pluto's atmosphere during solar occultation.

Global spectral maps of Pluto and Charon in the near-infrared will clarify and help answer several fundamental questions about this unique planet-moon system. How this pair originated is one problem to be addressed by the PFF mission. Pluto and Charon appear to have different surface compositions, suggesting differences in their evolution and interior structure. A better understanding of the surface composition should help to distinguish between

capture theories and those hypothesizing a giant impact and breakup of a primordial body. The extent of Pluto's internal thermal activity is also not known. Pluto is often compared with Triton, which has a similar bulk density and appears to have a similar surface composition. With Triton, Pluto and Charon are the largest known bodies that can be examined to probe the history of the formation of solid planetary objects in the outer Solar System.

Under the current scenario, observations of Pluto and Charon will be begun a few hours before the closest approach of the spacecraft to Pluto. Charon will be mapped first, over a period of about 45 minutes at a spatial resolution of 10 km/second. Pluto will then be mapped in about 1.5 hours at a resolution of 7 km/second. The signal-to-noise ratio in the spectral maps will be about 100. The spectral maps will be compressed and stored in on-board memory to be returned to Earth over a period of many months.

LEISA is a joint effort between the Planetary Systems Branch (D. Jennings, D. Reuter, M. Flasar, D. Deming, G. McCabe, G. Bjoraker, V. Kunde) and the Solid State Device Development Branch (M. Jhabvala, P. Shu, V. Bly, J. Travis, S. Graham) at GSFC.

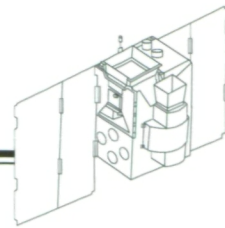
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Sponsor: Office of Space Science

Dr. Donald Jennings has 17 years of experience at GSFC. A planetary physicist in the Laboratory for Extraterrestrial Physics, Dr. Jennings is interested in the infrared spectra of the atmospheres and surfaces of planets, moons, and comets. Dr. Jennings holds a PhD in Physics from the University of Tennessee.

Dr. Dennis Reuter has 13 years of experience at GSFC. An astrochemist in the Laboratory for Extraterrestrial Physics, Dr. Reuter is interested in the chemical compositions and processes in Solar System objects. Dr. Reuter holds a PhD in Chemistry from the University of California, Berkeley.



RADIATION HARDNESS OF HIGH-TEMPERATURE SUPERCONDUCTOR FILMS

INFRARED SPECTROSCOPY is a powerful tool for the characterization of physical systems such as galactic, stellar, and planetary atmospheres and surfaces. When spectral coverage is required to long wavelengths, i.e., tens to hundreds of microns (depending on operating temperature), a thermal-type infrared detector such as a bolometer is required. A bolometer is essentially a sensitive, rapid-response thermometer coupled to an efficient radiation absorber. Bolometers become more sensitive and faster at lower temperatures; hence the requirement for liquid-helium cryogenics, as on Infrared Astronomy Satellite (IRAS) and COBE. Very valuable information on planetary atmospheres and surfaces has been returned by infrared instruments aboard the Pioneer and Voyager spacecraft, among others. For the outer planet missions in particular, it is somewhat ironic that the thermal detectors utilized have been devices originally developed for 300-K operation, with no substantial improvement in signal-to-noise at temperatures readily achievable by passive, radiative coolers (80 K and lower for Saturn and beyond). Future missions to the outer planets would greatly benefit from infrared detectors more sensitive than those employed to date.

High-temperature superconductor (HTS) transition-edge bolometers are particularly appealing for outer space applications because of a chance coincidence of transition temperature T_c (~90 K for $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$) and operating temperatures of passive coolers. Space applications provide particular challenges to HTS material properties, with conditions ranging from high vibration and acoustic environments at launch, to high vacuum, ionizing radiation, and temperature cycling during missions which can last longer than 10 years, as in the case of outer-planet missions. While there have been hundreds of reports discussing the effects of ionizing radiation on T_c and critical current J_c , the effect of ionizing radiation on excess noise remains largely unreported.

Consequently we set out to measure the effect of ionizing radiation on $1/f$ noise. We have chosen to do our initial testing with α -radiations since they are present in both primary and secondary radiation, simulate well the dominant ionization effect, and because γ -ray testing is very standardized. At NIST/Boulder, YBCO films 150 to 200 nanometers (nm) thick were deposited by an *in situ* laser ablation process onto CeO_2 -buffered sapphire substrates, and patterned into areas with four silver contact pads each. Electrical characterization and γ -ray exposure were done at GSFC. Four-contact/four-wire noise data were taken before and after radiation exposure. Using a ^{60}Co source, a total dose of 100 krad (Si) was deposited over 40 hours while the HTS was held at 77 K in vacuum to minimize thermal annealing effects. For small-area films characteristic of use in bolometers, no change was noted in the excess noise, nor was any change noted in transition width or in T_c . Thus, a transition-edge bolometer would be expected to be robust with respect to damage by 100 krad of γ -radiation.

Numerous reports on displacement damage (due to electrons, protons, heavy ions, etc.) have shown changes in properties such as T_c and J_c , and there is one report on the effect of heavy ions on excess noise. We plan next to assess the effect of these other constituents on transition-edge $1/f$ noise, investigating the effects both of point defects (due to protons and neutrons), and of columnar defects (due to heavy ions).

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Dr. John Brasunas holds a PhD in Physics from Harvard and is an astrophysicist with 9 years of service at GSFC. His professional interests include infrared detector and spectrometer development, and high-resolution spectroscopy of the atmospheres of Earth and other planets.

PREDICTING PARTICLE FALLOUT IN A SPACECRAFT INTEGRATION FACILITY

THE CORRELATION between the cleanliness of air in a clean area and the particulate fallout a component might experience is a tenuous one. Frequently people have asked, "How long does it take for a surface to reach Level X when placed in a cleanroom with measured air cleanliness Class Y?" Otto Hamberg, in his 1982 paper "Particulate Fallout Predictions for Clean Rooms" (*The Journal of Environmental Sciences*, May/June 1982, p. 15) attempted to address the cleanliness-fallout rate correlation, but his conclusions are weakened by his 95-percent confidence interval for fallout rates (given a certain air cleanliness): this interval spans two orders of magnitude. Nonetheless, Hamberg does offer some useful ground rules for predicting particulate fallout.

There are two standards which are vital for describing air cleanliness (particles per unit volume) and surface cleanliness (particles per unit area). They are FED-STD-209D, *Clean Room and Work Station Requirements, Controlled Environments* and MIL-STD-1246B, *Product Cleanliness Levels and Contamination Control Program*. FED-STD-209D defines airborne particle counting requirements and cleanroom classifications. Across a certain range, the cleanroom air quality *Class* is equivalent to the number of particles $\geq 0.5 \mu\text{m}/\text{ft}^3$. MIL-STD-1246B defines a surface cleanliness *Level*, and refers to required measurement techniques. It is helpful to remember that a given Level refers to surface cleanliness and that a given Class refers to air cleanliness.

A study, the results of which were presented this year, was done to test the applicability of Hamberg's guidelines for predicting particle fallout in a GSFC cleanroom. The experimental method involved the simultaneous collection of air cleanliness and surface fallout data in the Space Systems Development Integration Facility (SSDIF). The presence of ongoing activity, the existence of necessary monitoring equipment, and its importance to future GSFC flight projects made the SSDIF a logical choice. With the assistance of the operations staff (NSI/GSFC Code 754), we chose two specific study sites in the SSDIF. One was expected to have only occasional activity; the other, daily (weekday) activity. A total of eight silicon wafers were prepared for exposure in the two areas. Wafer exposure times varied from 1 to 3 weeks. Background particulate counts were obtained, the wafers were placed in covered glass petri dishes, taken to the SSDIF, and the lids removed. Air cleanliness near the

wafers was monitored and recorded. After the exposure period, the dishes were covered and the wafers taken to an image analysis lab for particulate counting. In Hamberg's report, the number of particles $5 \mu\text{m}$ was used to describe the cleanliness of the cleanroom air. Due to technological improvements in the past 10 years and due to the cleanliness of the SSDIF's air, counting particles $0.5 \mu\text{m}$ is more appropriate. For the eight periods in this study, air cleanliness Class averages ranged from 2 to 63. Not surprisingly, the vast majority of airborne particles detected were generated by a few particle-generating events. The typical surface cleanliness of the wafers ranged from Level 100 to Level 700. Seven of the eight data points collected lay either within Hamberg's 68-percent confidence interval or within an extrapolation of these intervals into the cleaner air class typical of the SSDIF. These data fit within the broad range of data collected by Hamberg or within a simple extrapolation made to accommodate the cleaner conditions found in the SSDIF.

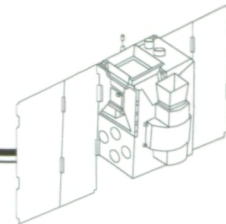
Hamberg made specific recommendations about predicting fallout rates. For a cleanroom like the SSDIF, he advised use of the minimum 68-percent confidence limit to determine a conservatively high estimate for the fallout rate. All of the SSDIF fallout rates are higher than Hamberg's estimates. This is likely due to the differences in data collection technique. While we attempted to comply with Hamberg's suggestions for extension of his work, we now advise establishing new predictive guidelines unencumbered by the problems of comparing local data with Hamberg's data (gathered using very different methods). Also, rather than attempting to predict fallout for any clean-room of a certain type, predictive guidelines for a specific clean area may be a more realistic goal.

Mr. James Duran, formerly of Code 724/EER Systems, participated in all phases of this study. The SSDIF operations staff (Code 754/NSI) provided indispensable support as well.

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Sponsor: Office of Safety and Mission Assurance

Mr. Van Sant is an electrical engineer in the Materials Branch at NASA GSFC. He has been involved with several applications of image processing to materials tasks, including the automation of particle counting.



AN INTEGRATED POINTWISE NDE IMAGING SYSTEM

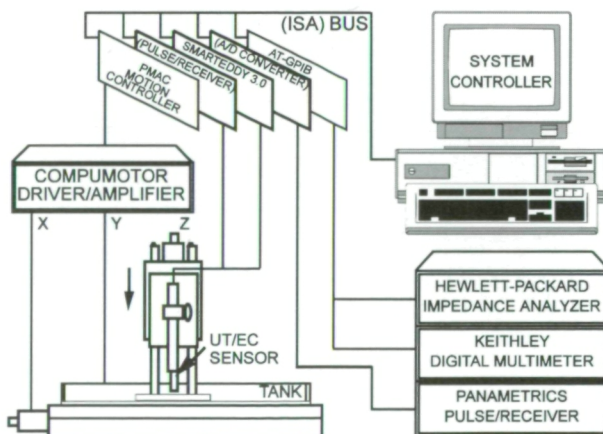
THE PERPETUAL DEMAND for improved manufactured system capability and performance often dictates increased complexity in the areas of component design, material usage, and fabrication processes. Mission success can be better achieved by employing an advanced concurrent engineering approach which includes design for performance, manufacturing, and testability (i.e., for process monitoring, quality assurance, and in-service health monitoring of all critical components). Nondestructive evaluation (NDE) methods provide the evaluation engineering technology to meet structural reliability requirements and other quality-assurance demands, without affecting the integrity of the item being tested. Imaging methods that directly correlate measured NDE parameters with component coordinates are generally the preferred method of data acquisition and presentation. Ultrasonic and eddy-current techniques are the two most widely utilized NDE methods that can be readily implemented for qualification, monitoring, and control of manufacturing processes. Ultrasonic C-scan and eddy-current imaging systems are pointwise evaluation systems. These systems rely on a mechanical scanner to physically maneuver a probe relative to the specimen point-by-point to acquire data and generate images. Recent advances in computer and electronic technology have facilitated the development of engineering workstations based on personal computers (PCs) with application-specific plug-in expansion boards. IBM-PCs and their compatibles are gaining in popularity as system controllers and host computers for many mechanical control, instrument control, and signal processing boards. Since the ultrasonic C-scan and eddy-current imaging systems are based on the same pointwise scanning and data acquisition mechanism, the two systems can be integrated using the same PC platform.

We have developed an IBM PC-based combined ultrasonic C-scan and eddy-current imaging workstation including a common mechanical control, data acquisition, and image processing software. The hardware of the system has three major components: a system controller, a mechanical scanner, and NDE sensors and instruments. A CompuAdd 325 PC (IBM-PC, 386-compatible) is used as the system controller. A Delta Tau Data Systems Programmable Multi-Axis Controller (PMAC) motion controller card, Compumotor Plus drivers/motors, and a Daedal X-Y linear table with incremental linear encoders

make up the mechanical scanner. For the ultrasonic instrument subsystem, an 18"W x 30"L x 6"H plexiglas immersion tank is mounted on the surface of the mechanical table. A Panametrics 5052UA pulser/receiver with gated peak detector and a Keithley 196 System Digital MultiMeter (DMM) act as the drive and measuring instruments, respectively, for the ultrasonic signals. For the eddy-current instrument subsystem, a Hewlett-Packard 4194A Impedance/Gain-Phase Analyzer provides the signal drive and measurement capabilities for the eddy-current signals. An SE Systems SmartEddy 3.0 eddy-current plug-in instrument is also implemented in the system for other eddy-current applications.

The system controller interfaces with the mechanical scanner, using the PMAC controller card and the SmartEddy 3.0 through the industry-standard architecture (ISA) PC-bus. The gate-peak-detected ultrasonic amplitude data from the system DMM, or the eddy-current impedance data from the Impedance/Gain-Phase Analyzer is transferred to the system controller through an IEEE-488 interface bus. This interface bus is managed by a National Instruments AT-GPIB controller card, which also resides on the PC-bus. A sketch of the system is shown in the figure.

The ideal digital pointwise imaging system would command the scanner to scan at a desired speed and obtain measurements at the desired positions on-the-fly. There-



A sketch of the integrated ultrasonic and eddy-current imaging system and its components.

fore, we developed a firmware approach which uses interrupts generated by the mechanical system at the desired positions to trigger and initiate the data acquisition routine. The control program enables the PMAC to generate interrupts in the system controller as trigger signals to initiate data reads. The scan routine downloads the scan parameters to the PMAC memory along with the position of the first measurement. The remainder of the measurement positions are calculated in real-time during the scan, relative to the starting position.

While scanning, the PMAC microprocessor constantly compares the real-time probe position from the encoder feedback with the precalculated acquisition coordinates. An interrupt is generated by a Programmable Interrupt Controller (PIC) on the PMAC card and received by another PIC in the PC when the positional conditions are met. The PC PIC subsequently generates an interrupt to PC CPU. This interrupt is used by the CPU as the trigger signal to invoke the data acquisition routine, and to synchronize other events. The PMAC PIC continually generates interrupts until the scan routine is completed. Since the encoders are independent of the mechanical drives, the interrupts are generated at precisely the desired coordinates.

There are many advantages associated with the combined system. It has: (1) eliminated duplication of computer and mechanical hardware; (2) unified data acquisition, processing, and storage software; (3) reduced setup time for

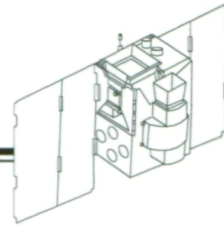
repetitious ultrasonic and eddy-current scans; (4) increased versatility and flexibility; and (5) improved system efficiency. However, there is a minor drawback: the system can only perform either ultrasonic C-scan or eddy-current imaging at a given time, as each inspection procedure requires calibration of the instruments. The throughput may be compromised if continual changeover between ultrasonic and eddy-current scans were to be implemented.

IBM-PC based manufacturing, test and measuring systems are routinely being developed, introduced and implemented in various industries. This concept can be adapted to many engineering systems by integrating related PC-based instruments into one multipurpose workstation such as dispensing, machining, packaging, sorting, and many other industrial applications.

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Sponsor: Office of Safety and Mission Assurance

Dr. James Chern is a materials engineer in the Materials Branch, Assurance Technologies Division, Office of Flight Assurance. He earned his PhD in Physics from the College of William and Mary in 1981. Dr. Chern has been at GSFC for 4 years. His prime responsibility is research, development, engineering, and application of NDE for composites and other spaceflight materials and structures.

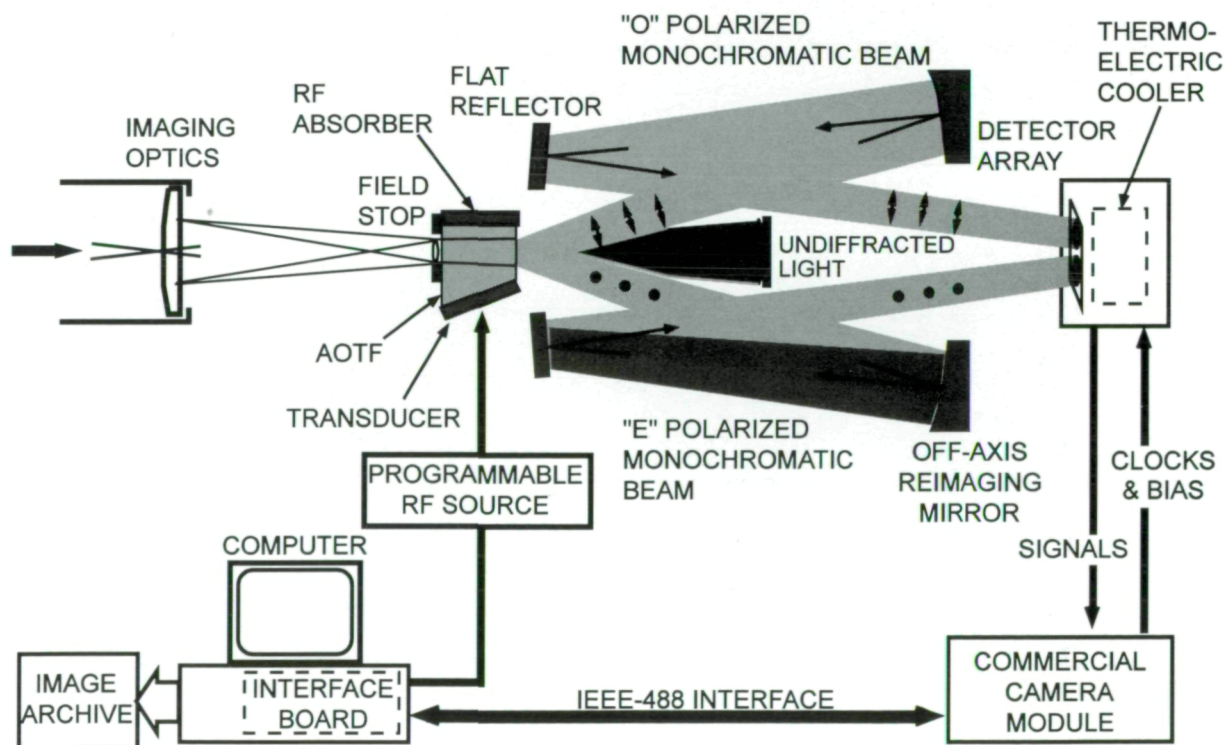


IMAGING SPECTROPOLARIMETRY USING ACOUSTO-OPTIC TUNABLE FILTERS

A NEW CLASS of highly compact imaging spectrometer produces two-dimensional, narrowband images in orthogonal polarizations, with broad continuous tuning and no moving parts. This is accomplished by imaging light through an electronically tuned, non-collinear acousto-optic tunable filter (AOTF). It operates by coupling an RF signal to a piezoelectric transducer which is bonded to the AOTF crystal. This produces a traveling phase grating and symmetrically diffracts orthogonally polarized beams at one select wavelength which satisfies a specific momentum-matching condition in the crystal. These two beams can be separately re-imaged. Tuning is accomplished by changing the frequency of the RF source.

A handful of acousto-optic materials have been used successfully to demonstrate operation from ultraviolet to thermal infrared wavelengths, with a range of efficiencies. Tellurium dioxide (TeO_2) AOTFs, the most mature and commercially available devices, now routinely demonstrate:

- spectral coverage from 400 nm to beyond 4 μm ;
- aperture dimensions of 1 cm x 1 cm, and an angular field-of-view of 6°. Larger fields-of-view are possible if only one polarization state is re-imaged;
- spectral resolving powers ($\lambda/\Delta\lambda$) as high as 1,000;
- continuous tunability over a factor of two in wavelength (e.g., 400 to 800 nm, or 1 to 2 μm) by changing the applied RF frequency. Wider device tunability is achieved using multiple transducers;
- single polarization efficiencies exceeding 70 percent over the full tuning range, and polarization isolation between the output beams which exceeds 1:10³;
- RF input power requirements less than 1 watt at visible wavelengths. However, the input power required for constant efficiency increases dramatically at longer wavelengths.

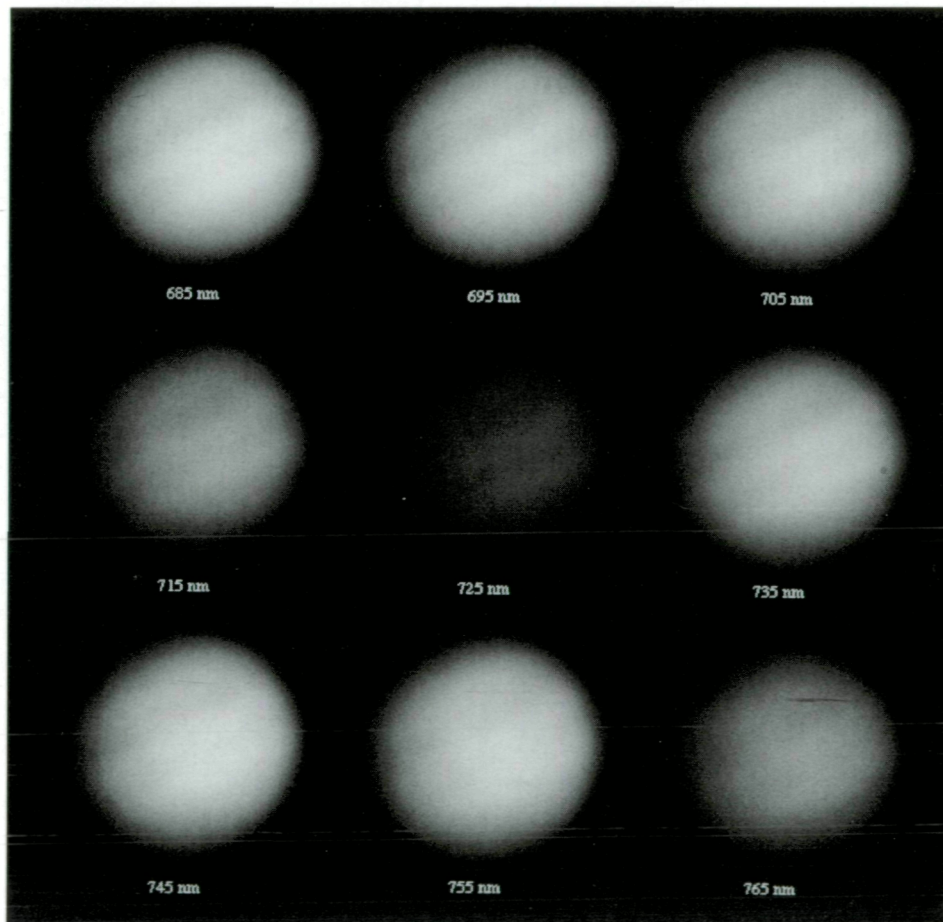


Block diagram of an AOTF imaging spectrometer developed at GSFC.

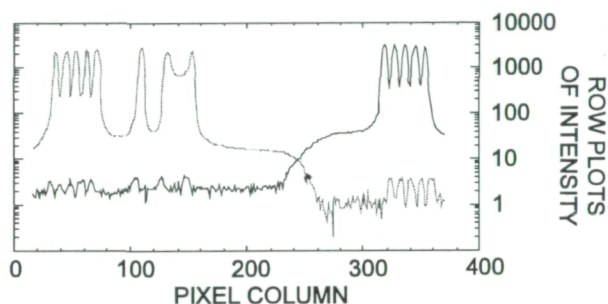
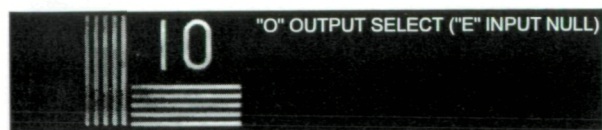
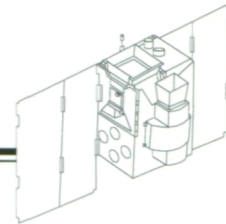
Their small size and fully solid-state operation makes TeO_2 AOTFs excellent candidate tuning elements for small space- and Earth-sensing payloads, where an entire multi-band instrument may be restricted to less than several kilograms and 10 watts of input power. The ability to rapidly select new wavelengths and the advantage of electronic shuttering adds important new capabilities.

An AOTF camera has been successfully demonstrated at GSFC using a TeO_2 AOTF, and the simple relay mirror configuration shown in the first figure. Light is imaged onto a field stop at the input face of the crystal, which is located at one focus of an elliptical relay mirror. The AOTF symmetrically diffracts the incoming "E" polarized light in one direction, and the "O" input light in the other. Both

beams are re-imaged by off-axis elliptical mirrors. Tilted flat reflectors direct the focus to a plane behind the mirrors, where it is convenient to place a commercial CCD camera head. The flat reflectors can be adjusted to place the orthogonally polarized images side-by-side on a rectangular CCD array (e.g., a Thompson CCD with 576 X 384 format). The operating wavelength is tuned by automatically changing the RF drive frequency, which means that the instrument can function either in the imaging mode at one wavelength, or as a scanning spectrometer by sequencing through a series of wavelengths. Its flexibility is limited by the specific camera design and the operating software. This optical configuration maintains axial symmetry and shallow reflection angles so that both polarization states see the same optical throughput. The use of



Spectral image sequence of Jupiter using one of the polarized beams. The central image lies at the center of a Jovian atmospheric CH_4 absorption band, so the reflectivity of the planet is noticeably dimmer.



Test target images showing the high polarization selectivity of the AOTF. Isolation between the side-by-side images exceeds $1:10^3$.

non-transmitting elements eliminates the need to refocus as the operating wavelength is changed.

The last two figures demonstrate the spectral imaging and polarization selection features of the camera. As shown in the second figure, a series of narrowband ($\Delta\lambda < 1.5$ nm) images of Jupiter were acquired using only one of the beams, with the spectrometer attached to the 0.9-m reflecting telescope at the Goddard Geophysical and Astronomical Observatory. The sequence, taken at 10-m steps, brackets a well-known CH_4 absorption band in the Jovian

atmosphere at 725 nm. The planet's reflectivity appears noticeably lower at this wavelength, as shown in the central image. The image quality is limited by atmospheric "seeing," and not by the AOTF or optics.

High polarization selectivity is revealed in the two successive test target images shown in the third figure. A Glan-Thompson prism was placed in the input light to select first one state (top) and then the other (bottom), with the AOTF acting as an analyzer. As shown in the intensity profiles, the device isolates the two states to a level exceeding $1:10^3$, which corresponds to the adjustment limit of the input polarizer.

These devices are not without some inherent difficulties. Because of the small deflection angle, a "science quality" polarimetric AOTF camera must be carefully designed to re-image the diffracted beam while rejecting stray light from the intense, broadband light that passes undeflected through the crystal. This requires foreoptics and high-quality surface polishing to minimize stray light from all optical elements, including the AOTF itself.

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BALL BURST TEST AS A TOOL FOR DISCRIMINATING AMONG BALLOON FILMS

IN THE EARLY 1980s, balloon materials were identified as the most probable cause of balloon failures. Since then, the Balloon Projects Branch has been conducting a comprehensive investigation into determining the cause(s) for these failures. The purpose of this article is to present an assessment on the validity of the ball burst toughness test as a balloon film discriminator.

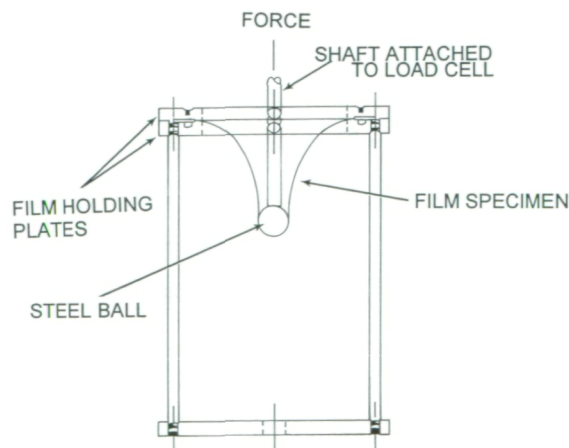
The toughness of a material is a measure of the work per unit volume required to cause fracture. It can be measured graphically as the area under the stress-strain curve. Uniaxial and ball burst toughness have been investigated and compared for several commercial polyethylene films. The films have been used by the U.S. and other countries in helium-filled heavy-lift balloons from 1970 until present. The success levels of these films over this period varied from essentially 0 to 100 percent for balloons of volumes up to 1.13 million cubic meters.

Uniaxial toughness was measured in both machine (MD) and transverse (TD) directions using a rectangular sample 25.4 mm wide by 50.8 mm gauge length. The uniaxial measurements were collected on a standard electromechanical testing machine (Instron Model 4505). A 100-newton load cell (maximum capacity) was used for data collection. The uniaxial specimens were held in the machine using a set of self-tightening elastomeric grips. The ball burst test is used to measure the toughness or the resistance to breakage of the films under nearly biaxial conditions. Ball burst measurements were conducted using the above Instron system equipped with a ball burst fixture. The test fixture was made of two plates with 127-mm-diameter holes. The film was placed between the two plates and held in place by drawing a vacuum between the two plates causing atmospheric pressure to clamp the film and plates in place. The vacuum channels were surrounded with two O-rings to assure enough vacuum to hold the film and plates in place. The lower plate was attached to the base by a set of supporting rods that allow enough clearance for film deformation. The fixture was attached to the machine crosshead through a standard pin-type clamp. A ball, 50.8 mm in diameter, was used to deform and rupture the specimen in the test fixture. The ball was mounted on a shaft that, in turn, was attached to the load cell of the machine. A schematic of the ball burst test fixture is shown in the figure. Both uniaxial and biaxial toughness measurements were conducted at 23 °C

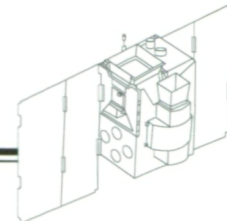
room temperature and at -80 °C low temperature. The cross-head speed was maintained at 508 mm per minute.

The performance of each film in flight was measured by calculating, from the available data, the maximum stress index (MSI) for all flights of balloons made of that particular film. The stress "index" was developed in 1984 to establish the relative stress magnitudes for any altitude. Further studies and failure investigations have shown a correlation between the relative magnitude of the stress "index," failure rate, and the point of observed failure. In January 1985, the stress index was instituted as a design parameter for all NASA balloons.

The uniaxial and biaxial toughness of the eight commercial balloon film materials studied along with their in flight performance are summarized in the table. AF-E, FF and X-124 exhibited high toughness in the uniaxial and ball burst tests at both room and low temperatures. Their performance based on the stress index data and their flight success history appears to correlate with their measured toughness. AF-C and BIF have shown, in general, low toughness, as exhibited by their low stress index and high percent failure. The BIF, in particular, has experienced 100-percent failure when flown at night and 18 percent when flown during the day. This appears to be attributed to its extremely low uniaxial and ball burst toughness at -80 °C. Although it had high ball burst toughness at both room and low temperatures, SF-372 exhibited low tough-



Schematic representation of the ball burst fixture.



Balloon performance as compared to maximum observed stress index (MSI) and film toughness (MPa).

Film	MSI (MPa)	% Failure	Tough. (RT)		Tough. (LT)		Tough. (BB)	
			MD	TD	MD	TD	RT	LT
AF-C	21.52	66	81	96	81	139	31	38
AF-E	26.52	6	171	175	248	222	50	73
SF-372	26.52	0	237	287	221	66	65	57
FF	20.94	10	287	241	365	202	60	65
SFI	23.40	56(N);10(D)	157	135	133	198	28	52
X-124	21.75	3	233	274	329	271	56	58
SF-85	19.82	29	137	131	242	154	32	36
BIF	17.68	100(N);18(D)	82	128	124	12	24	35

ness in the uniaxial at -80 °C. This result was anticipated, since SF-372 usually exhibited low deformation in the transverse direction at -80 °C.

Results indicate that the uniaxial toughness test is not as clear a discriminator test for thin films as the biaxial ball burst test. Although general trends can be noted, the directionality of the uniaxial test and film provides additional variability in the data, whereas the biaxial test clearly differentiates between the films.

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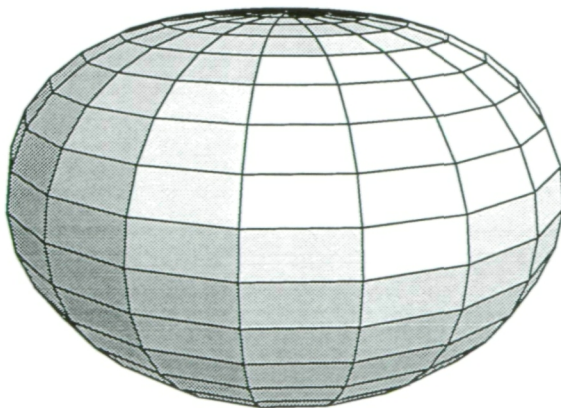
MATHEMATICAL MODELING OF ENERGY MINIMIZING OFF-DESIGN SHAPES OF LARGE SCIENTIFIC BALLOONS

CURRENT DESIGN CRITERIA for large scientific balloons are determined by conditions that the balloon will encounter at its float altitude. Usually, the shape of the balloon is modeled by a system of nonlinear differential equations called the Σ Shape, or Smalley equations. Boundary conditions are based on factors such as payload, balloon film weight, volume, and float altitude. Solutions at float and during ascent are assumed to be axisymmetric, and the hoop stresses are assumed to be zero. At altitudes below float, all excess material is assumed to be contained within a rope section that hangs beneath the base of the balloon. The first figure presents a shape at float (the design shape) and the second figure presents a shape with a rope section. Based on observations of actual balloons, it is clear that the typical shape of a balloon is not axisymmetric and hoop stresses are not zero.

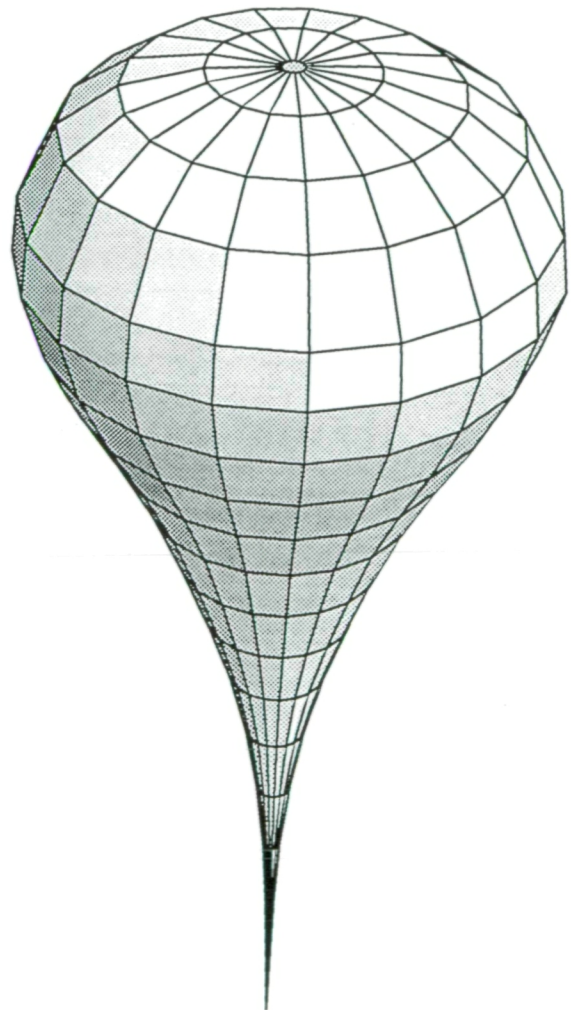
To model accurately the behavior of a real balloon, it is essential that the axisymmetric shape assumption be dropped and that the model reflect observed features. In particular, fold-like features need to be incorporated into the mathematical model. A new approach has been developed for constructing a balloon shape based on the inextensibility of the balloon film, preservation of balloon surface area, and a set of rules that model how excess material must fold away.

Three types of fold-like features have been observed in real balloons: (1) clefts - V-shaped, indented formations

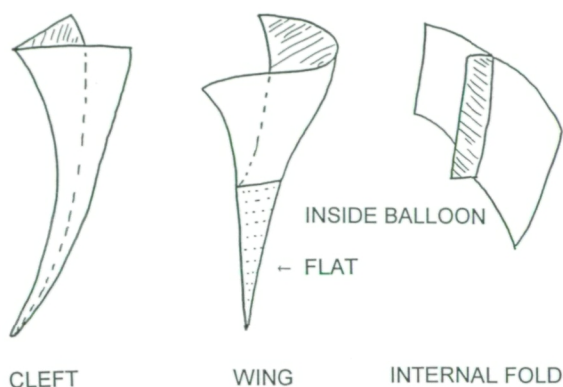
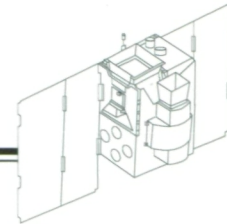
running from top to bottom of the balloon (see the third figure, part a); (2) wings—flat sections, starting near the base of the gas bubble and running to the bottom of the balloon (see the third figure, part b); and (3) internal folds—flat sections, folded inward, directed toward the center axis of the balloon, running parallel to the load tapes, and contained within the area defined by the gas bubble (see the third figure, part c). By requiring that the off-design shape have a certain type of symmetry, preserving the lengths of circumferential balloon fibers, and requiring that excess fiber material be contained within



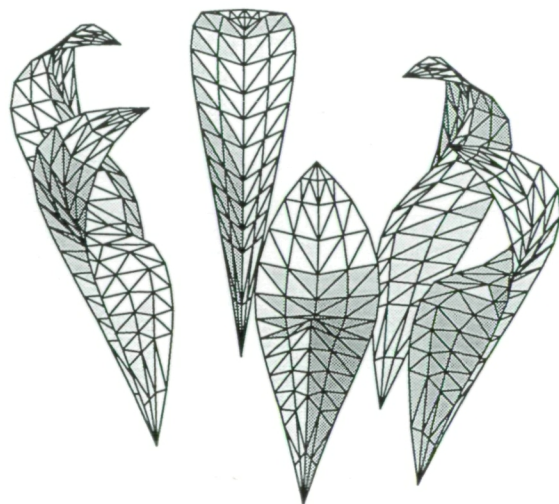
Smalley shape at float.



Smalley shape below float with rope section.



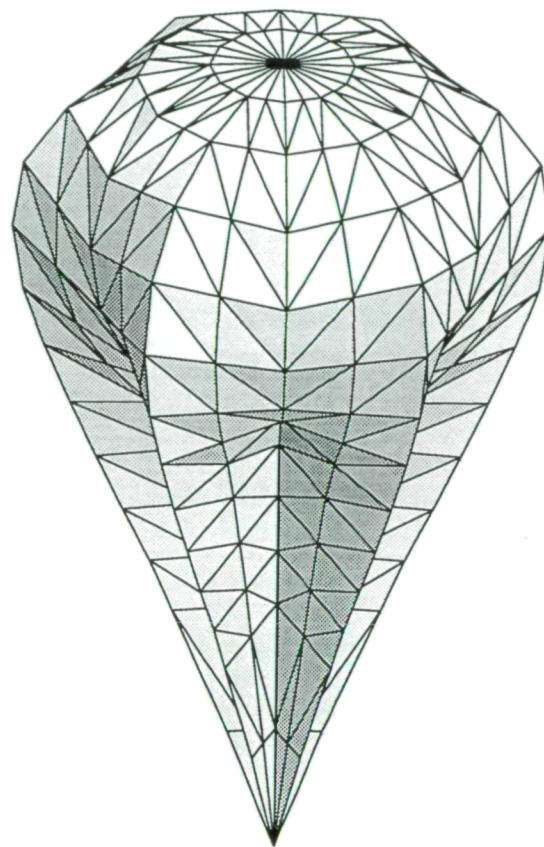
Types of fold-like features observed in real balloons.



Off-design components.

an internal fold running along the hook profile, it was possible to construct an off-design balloon shape that had many features of an actual balloon. The fourth figure shows the components of a complete off-design shape, and the fifth figure shows the complete shape.

The current body of scientific literature on shape determination of large scientific balloons is limited, focusing on axisymmetric shapes. This was the first attempt to incorporate the folding of excess material into a geometric model for shape determination. The initial work done was based on geometric considerations and is used to define the initial estimates for an equilibrium shape. The balloon is approximated by a simplicial complex whose faces



A complete off-design shape.

are triangles. Each triangle in the complex is identified by its vertices, edges, and an orientation. The entire balloon is modeled as a set of facets. Some facets surround the gas bubble; others are contained in regions such as the internal folds or the flat wing sections.

The physics are then incorporated into the mathematical model by considering energy minimizing off-design shapes (EMODS) with each facet contributing to the total energy of the balloon configuration. The energy is computed in terms of certain surface integrals. Since the initial shape is discretized into a polyhedron, the vertices of the planar faces of the polyhedron are adjusted through a constrained minimization scheme that attempts to minimize the energy while at the same time satisfying certain material constraints. The objective is to determine the material distribution at altitudes during the ascent portion of a balloon flight that minimizes the total energy.

For this analysis, the balloon film is assumed to be inextensible. The total energy of an off-design balloon shape at a fixed altitude can be expressed completely in terms of surface integrals; the excess material in the gas bubble region is assumed to be contained within internal folds. Since the problem of determining EMODS is non-linear, it is not reasonable to expect that there is a unique shape at a given altitude. An EMOD shape is found from the critical points of the energy function that is constrained by the conditions that the volume of gas, meridional fiber lengths, and circumferential fiber lengths are constant. Since many balloon configurations are indeterminate, an additional assumption is needed to make the search for an EMOD shape well-posed. For this reason, our attention is restricted to symmetric solutions which have n planes of reflectional symmetry passing through the center axis of the balloon shape. More precisely, the minimization is carried out over all shapes that are invariant under the dihedral group D_n .

The preliminary results are promising, since they lead to shapes which are very similar to those observed in real balloons. This is a significant step beyond any currently available balloon shape model. Future improvements call

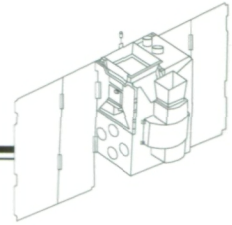
for a more refined analysis that will provide data for use as input into standard finite-element code for stress analysis, material configurations with clefts and configurations which are observed in the spool prior to launch, reinforcing caps, and load tapes. A further refinement might directly incorporate stress-strain laws and model the balloon film as an elastic material. In addition, other space structures might also be analyzed with this approach.

This work was done in collaboration with Dr. Frank Baginski, Associate Professor of Mathematics at George Washington University.

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DEVELOPMENT OF AN ABERRATED BEAM ANALYZER TO MEASURE WAVEFRONTS OF HUBBLE SPACE TELESCOPE OPTICAL SYSTEMS

THE HUBBLE Independent Verification Team (IVT) was chartered by the Engineering Directorate at GSFC to develop an independent method of verifying the optical performance of the corrective optics and ground-support equipment for the HST and associated instruments. In the case of the HST itself, spherical aberration exists in the wavefront because of the manufacturing flaw on the telescope primary mirror. This aberration is the now-unique "optical fingerprint" common to corrective and null optical systems, telescope simulators and instruments associated with the Hubble program. However, system- and component-level optical testing of wavefronts with this degree of spherical aberration can be difficult and time-consuming using conventional double-pass interferometric techniques.

The goal of the IVT was to develop a portable, compact, contamination-free instrument that was easy to align, thermally stable, self-calibrating, and which could be used at contractor facilities to non-invasively test a variety of optical systems. At the Jet Propulsion Laboratory (JPL), an all-reflective Hubble telescope simulator, the JPL stimulus, was built for performance verification and photometric calibration of the second-generation Wide Field and Planetary Camera (WFPC-II). The Corrective Optics Space Telescope Axial Replacement (COSTAR), was designed and built at Ball Aerospace Systems Group to correct the Hubble telescope wavefront for three of the first-generation instruments already on-orbit: the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), and the Goddard High Resolution Spectrograph (GHRS). The Refractive Aberrated Simulator (RAS) was designed and built at Ball to simulate the Hubble telescope to test the COSTAR optics.

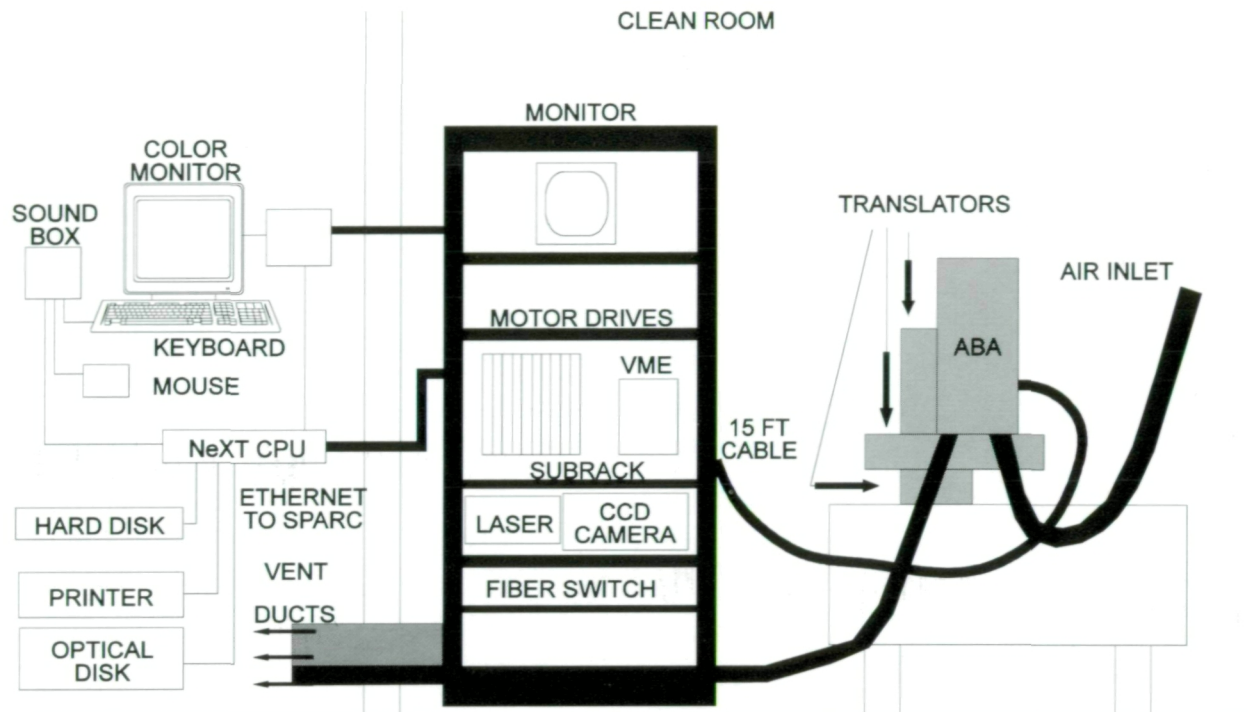
The diversity of the optical systems described above determined the final engineering requirements for the IVT hardware. The IVT instrument was required to measure wavefront and pupil parameters for optical systems with f-numbers ranging from $f/20$ (Hubble telescope simulators are $f/24$) to $f/40$ (corresponding to corrected COSTAR outputs for the FOC channel). Rapid development of a new instrument that could measure the wavefront error to an accuracy of $\lambda/40$ rms with a precision of $\lambda/100$ rms (at 632.8 nm) presented a challenging task. Another important requirement was that the instrument also have the capability to measure the exit pupil size, location, and obscuration ratio as well as chief ray angles. Typical pu-

pil distances ranged from 7.0 m for Hubble telescope simulators to 350 mm for the FOS-corrected channel of COSTAR. The software was required to perform a variety of sophisticated and complex wavefront and image analysis tasks. Image and data processing requirements included wavefront and image subtraction, rotation and scaling, x- and y-axis profiles of the point-spread function, pupil intensity profiles, pupil mask processing, standard FITS file formatting, and data archiving. The data analysis was to be performed in real time with quick turnaround.

After conducting a preliminary survey of a broad range of wavefront measuring techniques, the team finally settled on a unique type of Hartmann wavefront sensor as their best candidate for instrument development. In simplistic terms, a Hartmann test is traditionally implemented by covering a test mirror with a screen with regularly spaced holes, and a photographic plate is placed near the focus. When a perfect mirror is illuminated with white light, this results in an array of regularly spaced dots on the plate. When the mirror is imperfect, the spots are deviated from their ideal locations. These deviations are measured and related to the figure of the mirror being tested. We extended this approach to respond to the requirements outlined above, and produced the Aberrated Beam Analyzer (ABA), which was designed and developed jointly by a team consisting of representatives from GSFC, Adaptive Optics Associates, Inc., Fairchild Space, and Swales and Associates, Inc.

The ABA system is illustrated in the first figure. The ABA sensor head mounts directly on a set of external translators, which are used to provide 3-dimensional positioning of the ABA sensor head relative to the optical system being tested. Optical cubes (not shown in the figure) are mounted on the ABA head and translators for accurate alignment of the ABA with respect to the system being tested. An electro-optical controller (EOC) rack is stationed inside the cleanroom with the ABA, while a NeXT computer and peripheral devices are located in an adjacent control room. The computer communicates with the EOC rack via Ethernet cable connection to a SPARC board.

The ABA software handles all aspects of sensor calibration, data acquisition, data analysis and archival to an optical disk. The software package for the operation of



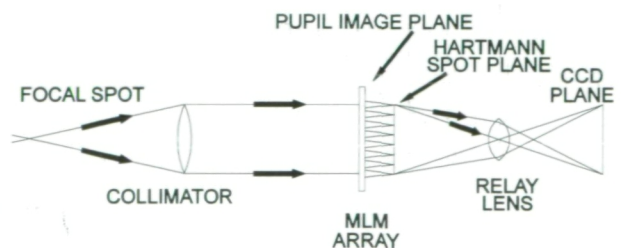
System layout for ABA.

the sensor is controlled by a scripting language and a graphical user interface (GUI). All pertinent parameters, such as CCD exposure time, internal monolithic lenslet module (MLM) stage positions, and external stage positions may be set via these interfaces. Internal motorized stages within the ABA sensor head set the optical system in the proper configuration for each phase of the measurement process. Pupil geometry is measured, the subaperture map on the detector is determined, sensor response is calibrated, and reference spot positions are recorded in a simple series of operations.

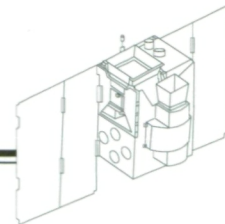
The wavefront sensor portion of the optics head is shown schematically in the second figure. The optical train consists of a broadband anti-reflection coated collimating lens, an array of microlenslets called the MLM, a relay lens, and a Photometrics scientific-grade CCD camera (1024 x 1024 array of 19- μm square pixels) with selectable exposure times. The collimator (140 mm focal length) serves to collimate the light from the focal spot under test and re-images the system exit pupil onto the MLM lens array. The MLM is the Hartmann test pupil dissector, a 60 x 60 array of 190- μm -sq microlenslets which divide the pupil image into many subapertures and form focal spots for

each. The relay lens re-images either the Hartmann spot pattern or the MLM plane (pupil image) onto the camera, depending upon the position of the camera/relay lens combination. The video signals from the camera are sent to the NeXT dimension board which digitizes the signal and grabs frames at the command of the processor. The digital data are passed to the processor for analysis.

An array of nearly ideal point sources that may be very accurately positioned near the collimator focus are provided for calibration. These sources are single-mode optical fibers fed by a HeNe laser. The ends of the fibers are mounted on a linear translation stage that allows the pre-



Optical layout of the ABA.



cise positioning of the fiber beam with respect to the optical axis of the ABA. The translation stage also allows positioning of the fiber sources either in front of or below the instrument aperture to alternate between reference source and test beam. When the reference source is in the path, the location of the centroid of each of the reference spots for each subaperture is measured. When the test beam is being measured by the ABA, the deviations of the test spots in the Hartmann spot pattern from the ideal reference spot positions are measured, and from these data, the wavefront slopes are computed.

In operation, once the sensor axis is aligned with the beam under test, the collimating lens is positioned to provide a roughly collimated beam to the MLM. The relay lens/CCD camera assembly is moved together until the MLM plane is conjugate to the camera focal plane. Then the collimator lens is positioned so that the MLM is conjugate to the system pupil. Data are then acquired with the camera and several custom software algorithms are used to accurately determine the pupil location and the position of each subaperture in the pupil. Knowledge of the position of each subaperture is critical for high-accuracy measurement of the wavefront. The camera is then moved back from the pupil image plane until the Hartmann spots are in focus. At this point in the process, the sensor must establish the detector subareas to be used for measuring the Hartmann spot positions. Further, it must associate each spot with the lenslet that generated it. Customized spot-tracking algorithms are used during this step of the measurement process.

At intervals during the measurement, the reference source is introduced and wavefront data are taken. In this way, the calibration of the zero point of the wavefront sensor is verified. At the start of the sensing run, a more elaborate calibration process is used. In this procedure, the spot locations arising from all four of the reference fibers are observed and compared to those of the central fiber source. The calibration of apparent spot motion to wavefront tilt is obtained by computation using the accurately known separations of the fibers and the collimator focal length.

Since the pupil image is directly recorded, the user can view and measure the intensity distribution and the pupil vignetting. The distance to the pupil may also be measured by noting the location of the MLM stage relative to the collimator when best pupil focus is achieved. However, this is not a very accurate way to measure pupil distances that are large compared to the collimator focal

length, as is the case for the 7-m distant pupils. For such cases, the parallax technique is used. In this procedure, two images of the pupil are obtained with the ABA translated along a well-determined baseline. The chief ray angles measured at these two locations are compared to yield a parallax angle. Using this angle and the known length of the baseline, the program calculates the distance to the exit pupil.

Once the calibration is complete, wavefront data are acquired. These data are processed using the calibration information to yield highly accurate Hartmann spot motions and from them, wavefront gradients. The Hartmann spot motion within each subaperture is determined using sophisticated tracing algorithms. The wavefront gradient data may be analyzed in several ways. The standard analysis provides for the decomposition of the wavefront into polynomial components. These polynomials are then used to calculate the optical path differences (OPDs). From the OPDs and the measured pupil intensity, the point-spread function, optical transfer function and modulation transfer function may be calculated. The encircled energy can also be calculated and plotted. The wavefront data may be manipulated in many other ways using the extensive analysis package provided on the processor. Hard copy of any of the data or analysis results is available at any time.

ABA design, development, breadboarding, fabrication, and extensive testing progressed over a period of approximately 12 months beginning in mid-January 1992, and culminating with the first field test at Ball Aerospace in mid-February 1993. During the test program, measured ABA test data were compared directly to predictions obtained from optical models. Based on this type of comparison involving extensive optical modeling, analysis and calibration, the ABA instrument has achieved an rms wavefront measurement accuracy of better than $\lambda/40$ rms with a precision of typically $\lambda/100$ rms at 632.8 nm. ABA measurements of pupil size, location, and obscuration ratio are accurate to within 1 percent. Chief ray angles can be determined to better than 30 arcsecond.

The development of this type of Hartmann wavefront sensor has proven to be extremely beneficial for the Hubble project. In late February of 1993, the ABA was used at Ball Aerospace in Boulder, Colorado, and at JPL in Pasadena, California, to verify that the RAS and the JPL stimulus correctly simulated the wavefront from the HST. The IVT returned to Ball Aerospace in July of 1993 to mea-

sure the corrected output of the COSTAR optics. This particular instrument will be used for testing of future Hubble optical systems.

It is our hope that the ABA can be used on other projects besides Hubble, whenever feasible. Although the system was specifically designed to operate at HeNe, nothing in the design precludes measurements with white light sources. There is no doubt that the optics industry will ultimately benefit from the ABA development, since commercialization of these types of Hartmann wavefront sensors is the wave of the future in optical testing.

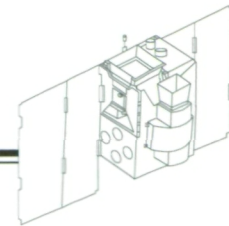
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Ms. Pam Davila is an optical physicist in the Optics Branch at GSFC, and has been employed full-time since 1989. She received a Master's from the Optical Sciences Center in Tucson, Arizona, and a Bachelor's in Physics from the University of Utah. She has worked on the optical design of grazing incidence telescopes, aberration-corrected holographic diffraction gratings, null lenses and telescope simulators, and the development of new optical testing techniques for ground-based testing of optical systems and components.

Mr. William Eichhorn is Head of the Optical Test Section in the Optics Branch, and has been employed at GSFC since 1967. Bill obtained an MS in Physics from the University of Maryland and a BS in Physics from Lowell Technological Institute in Massachusetts. Throughout his career, he has been involved in optical testing and alignment for a multitude of projects including COBE, HST, and CIRS.

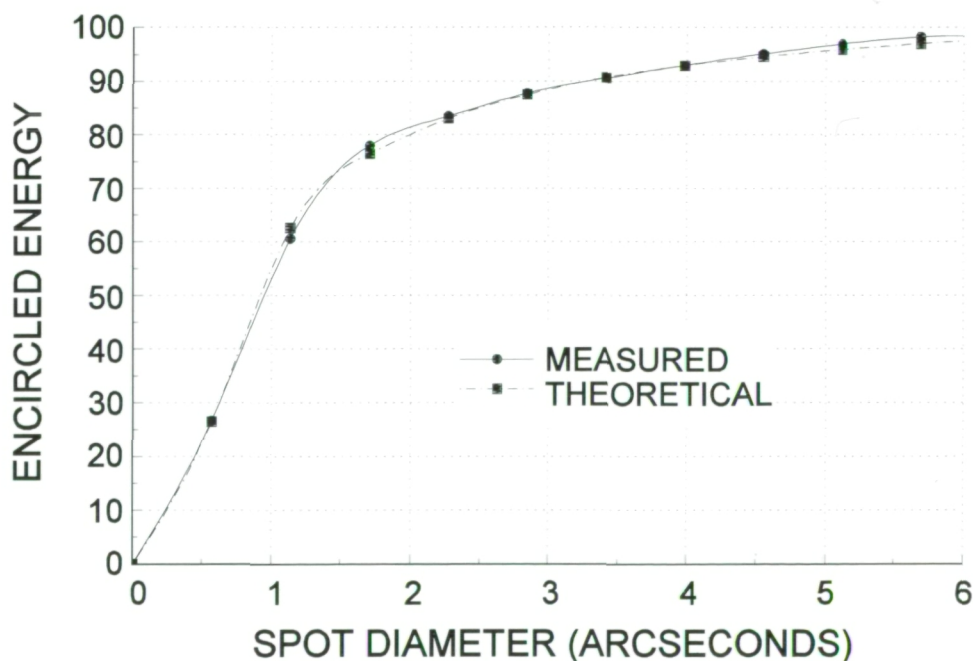


PERFORMANCE MODELING OF FAR-ULTRAVIOLET MIRRORS

RECENT ADVANCES in mirror materials and fabrication techniques now make it possible to achieve a high throughput and good image quality in the far-ultraviolet (FUV) wavelength region. To fully understand the relationship between mirror surface characteristics and image quality, we have developed Optical Surface Analysis Code (OSAC) and Metrology Data Processor (METDAT) software tools. With the help of these tools, we have modeled the imaging performance of FUV mirrors developed for the Solar and Heliospheric Observatory/Solar Ultraviolet Measurements of Emitted Radiation (SOHO/SUMER) instrument as part of the International Solar Terrestrial Physics Project (ISTP).

The OSAC and METDAT programs accomplish three functions: (1) derivation of instrument optical specifications, (2) instrument performance prediction, and (3) performance modeling of as-built optical components and instruments. METDAT is designed to analyze measured surface metrology data and to output the low-spatial-frequency polynomial coefficients and roughness parameters

for subsequent OSAC analysis. In other words, METDAT divides the surface error information into two parts: figure error and surface roughness. The figure error is fit into the surface error descriptors resulting in the low-frequency surface error model for OSAC's ray trace routine. From the surface roughness data, the METDAT program calculates the OSAC input parameters either for the autocovariance model or for the power spectral-density function model. OSAC's scatter routine is then used to evaluate the scatter characteristics of the mirror. The OSAC code provides a comprehensive analysis of optical system performance, including the effects of optical surface misalignments, low-spatial-frequency deformations (figure error), mid- and high-spatial-frequency deformations (surface roughness), and aperture diffraction. Both normal incidence mirror systems designed for infrared, visible and ultraviolet wavelength regions and grazing incidence systems designed for x-ray and extreme ultraviolet applications can be analyzed. The unique feature of the program is its capability to analyze scatter characteristics of the optical components over



Measured and theoretical encircled energy versus image spot diameter for a SUMER telescope mirror. The theoretical encircled energy is derived from mirror surface-deformation data using OSAC and METDAT programs.

a wide range of spatial frequency errors on the mirror surfaces.

The SUMER telescope mirrors are off-axis paraboloids fabricated with chemically vapor-deposited silicon carbide. The surface error characteristics of the mirrors were measured over all important spatial frequencies affecting the FUV performance using a Zygo Mark IV interferometer, a Bauer Model 200 profiler, and a Wyko Topo 2-D interferometer to measure mirror figure error, mid-frequency error, and microroughness, respectively. The encircled energy and wide-angle scatter performance of the mirrors were measured in our Diffraction Grating Evaluation Facility (DGEF) at the wavelength of 123.6 nm. The metrology data of the mirrors were analyzed by using the METDAT program to build corresponding surface error models. The resulting models were then input into the OSAC program to accomplish the performance analysis. The accompanying figure compares the measured and modeled encircled energy of one of the SUMER mirrors. The agreement between the curves is excellent. The 80-percent encircled energy diameter (a standard figure-of-merit) of this mirror is about 1.8 arcseconds. The measured and modeled wide-angle scatter of the mirror also agrees well up to 1,600 arcsecond from the central peak of the image.

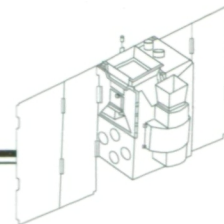
The METDAT/OSAC analysis revealed that the mid-frequency error of the SUMER mirrors is largely responsible for the degradation of the encircled energy performance. Without the mid-frequency error, the OSAC program predicted the 80-percent encircled energy of about 0.8 arcsecond. To improve the performance of the mirror, the mid-frequency error would have to be eliminated by improving the fabrication process.

METDAT and OSAC modeling was based on the mirror surface deformation data measured with our surface characterization instruments. We found excellent agreement between the directly measured and modeled results. To our knowledge, no other software tools can accomplish this task.

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Sponsor: Office of Space Science

Dr. Timo Saha is an optical physicist in the Optics Branch. He specializes in design, development, and theoretical analysis of FUV, EUV, and x-ray optical instruments. He received a PhD in Physics from St. Louis University, and has been at GSFC for 11 years.



HIGH-ALTITUDE LIDAR SYSTEM UTILIZES ADVANCED SOLID-STATE LASER TECHNOLOGY

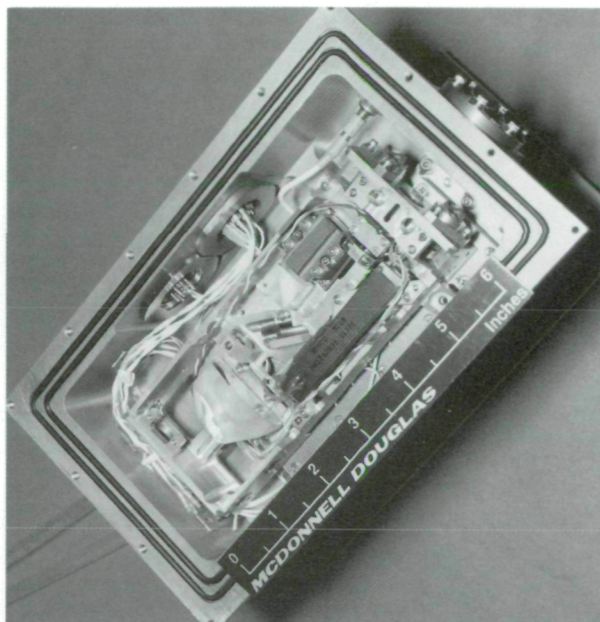
LIGHT DETECTION and Ranging (lidar) has become a powerful tool for studying the dynamics and chemistry of the atmosphere. Lidar operates by transmitting a short, intense burst of monochromatic light from a laser source, and measuring the time-resolved backscattering of photons as the pulse propagates through the atmosphere.

One of the most widely used lasers in lidar systems utilizes a flash lamp to optically "pump" an yttrium-aluminum garnet doped with neodymium (Nd^{3+}). This laser is commonly known as an Nd:YAG laser. In the pumping process for a laser, the flash lamp emits a broad spectrum of photons which are, at certain wavelengths, absorbed by the Nd^{3+} ions in the YAG. Using various techniques, a short, intense, monochromatic and highly collimated pulse of coherent photons may be generated. For Nd:YAG systems used in atmospheric lidar, this pulse is on the order of 10 nanoseconds long and has a peak power of several megawatts.

The broad spectral nature of the flash lamp emission means that much of the energy is not absorbed by the Nd^{3+} , and is converted to waste heat. This heat must be removed from the laser cavity with a coolant, usually water. Flash lamp-pumped Nd:YAG lasers have efficiencies (optical power out/electrical power in) of less than 0.1 percent. Airborne and spaceborne lidar systems require high average optical power output, thus, flash lamp-pumped lasers are unattractive for use on these platforms due to the requirements for water storage, circulation, and heat removal.

A recently developed technique for pumping lasers utilizes semiconductor diode lasers to pump Nd:YAG. The diode lasers themselves have efficiencies greater than 40 percent, and can be tuned to an absorption band of Nd:YAG. Typical efficiencies for these diode-pumped Nd:YAG lasers are 2 to 10 percent, up to one hundred times more efficient than flash lamp-pumped lasers. This means far less waste heat is generated, and a laser system with optical output power comparable to that of a flash lamp-pumped system may be operated without coolant.

GSFC and McDonnell Douglas Electronics Company have developed and flown a high-power, high-efficiency, all-solid-state laser in a high-altitude airborne lidar system (as shown in the first figure). The lidar instrument,



ER-2 laser diode-pumped Nd:YAG laser.

known as the Cloud Lidar System (CLS), is flown aboard a NASA ER-2, and profiles optical properties of clouds and aerosols below the aircraft. This system represents a major step towards the development of spaceborne atmospheric lidar instruments.

The new CLS laser, first developed by McDonnell Douglas as part of a Strategic Defense Initiative project, utilizes several thousand semiconductor lasers arranged in 2-dimensional arrays to optically pump a slab of Nd:YAG. The system generates 7-nanosecond pulses 10 to 20 times per second. Each pulse has a peak power of 25 megawatts. The fundamental output wavelength is 1,064 nm (near-infrared); approximately 50 percent of the energy at the fundamental wavelength is converted with an optical frequency doubler to 532 nm (green) energy. The laser system utilizes its own microcontroller (developed at GSFC) to control timing and to monitor its status.

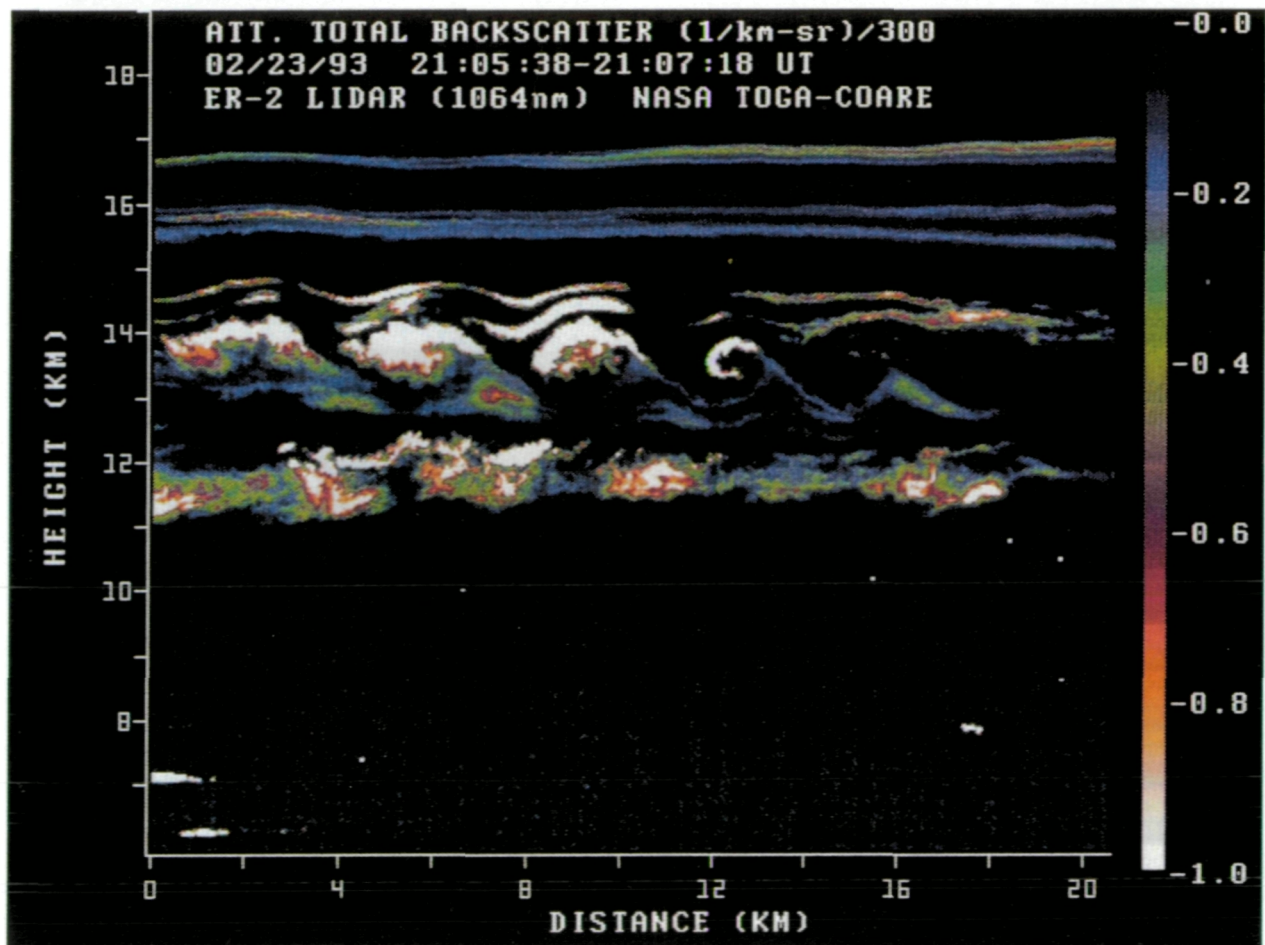
This laser system replaced an aging flash lamp-pumped Nd:YAG laser which had been flown with the CLS on the ER-2. With the new laser installed, optical power output capability increased four times, while the electrical power

requirement decreased ten times. The diode-pumped laser with all of its support electronics weighs one-third as much as the flashlamp-pumped version. When flown aboard the ER-2 aircraft, the entire CLS is mounted in a wing pod. A nadir window in the wing pod allows transmission of the optical signal. The ER-2 typically flies at an altitude of 65,000 feet (ft) (20 km). The wing pod itself is pressurized to 3.5 psi (24 kPa).

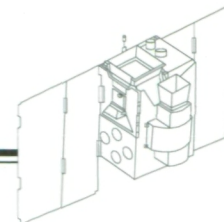
When powered on by the ER-2 pilot, the CLS, under control of its on-board microcomputer, autonomously acquires and stores lidar return signals, continuously profiling the atmosphere below the aircraft for up to 8 hours. The data

are stored on 8-mm magnetic-tape cartridges which are retrieved at the end of each flight by the ground support crew. During an 8-hour flight, 5 gigabytes of data are recorded.

The ER-2 Cloud Lidar System with the diode-pumped laser underwent integration and testing at NASA Ames Research Center in December 1992, in preparation for participation in the Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE). This multinational, coordinated experiment involved aircraft, ships, and instruments from several nations participating to study the effect of the Pacific



Sample data collected during TOGA/COARE field mission showing wave structure in cirrus clouds over the South Pacific due to shear winds. The horizontal axis represents distance along the ER-2 flight path. The vertical axis is altitude above sea level. White areas represent strong backscatter from the laser pulse, in this case due to scattering from water droplets in the clouds. Dark regions represent areas of little or no backscatter.



Ocean's warm-pool region on climate. The CLS provided many hours of valuable data on cloud structure over the study area (see the second figure). This study took place during January and February 1993.

Following this experiment, the ER-2 was immediately deployed in March and April 1993, as part of the Central Equatorial Pacific Experiment (CEPEX), coordinated by the Scripps Oceanographic Institute. The purpose of this experiment was to study the effects of clouds on heat transfer in the Pacific warm-pool region.

The ER-2 aircraft is a unique platform for atmospheric studies in that it is capable of getting above approximately 95 percent of the Earth's atmosphere. This capability also makes it ideal for testing concepts for future spaceborne instruments. In this case, the laser system performed well for over 150 operating flight hours.

This highly efficient, reliable technology shows great promise for future spaceborne atmospheric lidar instruments.

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Sponsor: Office of Space Science

Mr. John Cavanaugh has been employed at GSFC since 1984. He is currently an electronics engineer with the Experimental Instrumentation Branch of the Laboratory for Terrestrial Physics. Mr. Cavanaugh has been involved in the development and operation of a variety of airborne and ground-based optical remote sensing instruments including passive ocean-color sensors, atmospheric lidar systems, and laser altimeters. Mr. Cavanaugh has a BS in Electrical Engineering from the University of Maryland.

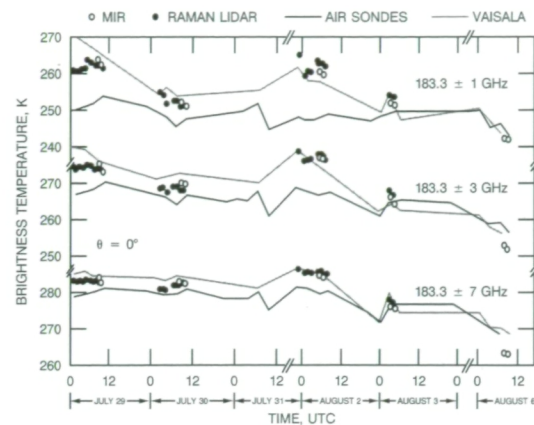
Dr. James Spinhirne received a BS in Engineering Physics from the University of Illinois, an MS in Electrical Engineering and a PhD in Atmospheric Physics from the University of Arizona. Dr. Spinhirne has been employed at GSFC as a scientist in the Laboratory for Atmospheres, with broad interests in remote sensing, instrument development, and atmospheric radiation and climate.

THE MILLIMETER-WAVE IMAGING RADIOMETER

A SIX-CHANNEL, airborne, total-power, millimeter-wave imaging radiometer (MIR) was built recently to provide precision measurements of atmospheric water vapor, clouds, and precipitation. The instrument is a cross-track scanner that has a 3dB beamwidth of $\sim 3.5^\circ$ and an angular swath of 100° . It measures microwave radiation at the frequencies of 89, 150, 183.3 ± 1 , 183.3 ± 3 , 183.3 ± 7 , and 220 GHz. These six frequencies were chosen so that the sensor could probe water-vapor concentrations at different depths of the atmosphere between the surface and ~ 10 -km altitude. The inclusion of a 220-GHz receiver makes this instrument unique; no other instrument has made atmospheric radiation measurements using this combination of frequencies. The instrument has two nearly perfect absorbers at widely different temperatures serving as calibration targets. Temperatures of these calibration targets are carefully monitored so that the scene brightness temperatures can be measured with an accuracy of ± 1 K.

The first MIR flight occurred on May 14, 1992, in the coastal regions of California. It was the first of five flights designed to validate/calibrate the Special Sensor Microwave/Temperature-2 (SSM/T-2) aboard the Defense Meteorological Satellite Program's (DMSP) F-11 satellite. Since then, the instrument has been flown for more than 130 flight hours on several missions that include the SSM/T-2 validation/calibration on both coasts of the continental U.S. (May to August 1992), and concurrent measurements with GSFC's surface Raman lidar system at the Wallops Flight Facility (July to August 1992), and TOGA/COARE in the western Pacific (January to February 1993). It has never experienced a failure in any of these flights, and high-quality data were acquired on all missions.

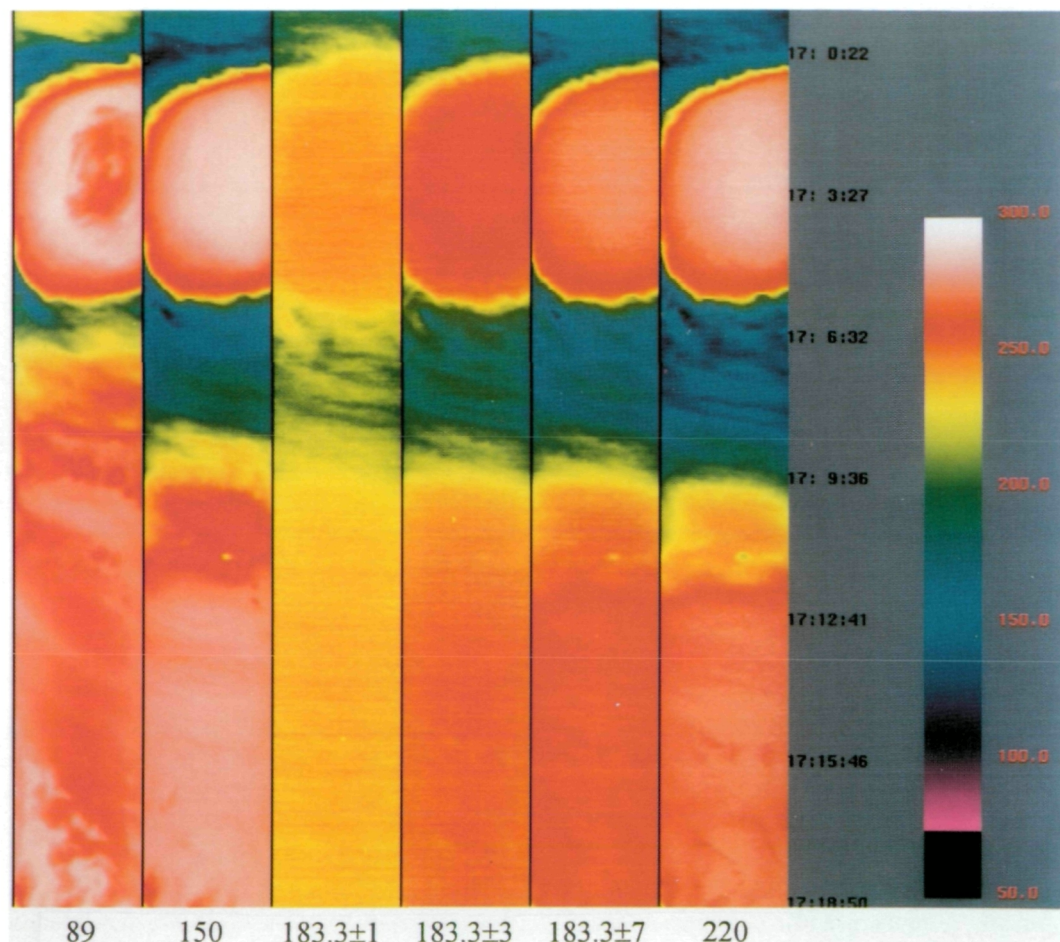
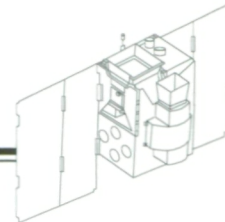
The first figure shows the results of 5 days of concurrent MIR and Raman lidar measurements in the vicinity of the Wallops Flight Facility. The measurements and calculations at frequencies of the three most opaque channels of the MIR are compared in this figure. Balloons carrying different rawinsonde packages were launched at 3-hour intervals during times of lidar operations to provide measurements of atmospheric temperature, relative humidity, and wind speed. The MIR measures the intensity of atmospheric microwave radiation in brightness temperature, while the Raman lidar measures water-vapor concentration in terms of mixing ratio. Radiative transfer calculations were performed on the measurements of Raman lidar and rawinsondes to arrive at



A comparison of brightness temperatures measured by the MIR and those calculated from the concurrent measurements by Raman lidar and rawinsondes.

the corresponding brightness temperatures for comparison with the MIR measurements in the figure. The lidar results from the last day of measurements were not included in the figure because it was cloudy at the time of lidar operation and the measured mixing ratio only extended from surface to ~ 3 km altitude. The agreement between the MIR and the lidar results is clear. The calculated brightness temperatures from the rawinsondes do not match well with either MIR or lidar results because of the well-known problems associated with rawinsonde humidity observations. The AIR sondes tend to overestimate at relative humidities < 20 percent, while the Vaisala sondes tend to underestimate at relative humidities > 80 percent.

The second figure shows the brightness temperature images acquired from the six channels of MIR when the ER-2 aircraft flew over the tropical cyclone "Oliver" on February 8, 1993. The storm center is located about one-third from the top of the image. Surrounding the storm center are bands of cold brightness temperatures showing scattering of microwave radiation by frozen hydrometeors. The scattering process is apparently frequency-dependent; the higher the frequency, the stronger the scattering of radiation. The measurements at the three 183-GHz channels do not quite follow this trend because the measurements of radiation at these frequencies are affected by strong absorption due to atmospheric water vapor.



The brightness-temperature maps of the tropical storm "Oliver" measured by the six frequency channels of the MIR.

We have begun to perform the retrieval of water-vapor profiles from the MIR measurements. In addition, we are also studying the characteristics of scattering processes from the MIR measurements over events like "Oliver." Retrieval techniques could be developed from these studies to estimate the profiles of the frozen hydrometeors. The MIR can also be used to monitor/assess the performance of an orbiting radiometer at comparable frequencies. Spaceborne sensors at the five lowest frequencies of the MIR have been built to provide large-scale estimation of water-vapor profiles. One of them (SSM/T-2) is already in orbit, and another (Advanced Microwave Sounding Unit B) will be aboard a NOAA satellite and launched in the mid-1990s. It is important to monitor the performance of these sensors to ensure adequate and reliable estimation of water vapor and other atmospheric parameters critical to the global energy and water cycle.

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Sponsor: Office of Mission to Planet Earth

Dr. James Wang is a senior scientist in the Microwave Sensors Branch of the Laboratory for Hydrospheric Processes. He has worked at GSFC for 16 years on the microwave remote sensing of soil moisture, water vapor, and precipitation. Dr. Wang earned a BS from the University of Washington, and an MS and a PhD in Physics from the University of Chicago. He is the Principal Investigator of the MIR, and has recently received a Group Achievement Award.

Mr. Paul Racette is an electronics engineer at GSFC where he has worked for 3 years. He received a BS and an MS in Electrical Engineering from the University of Kansas. He currently is pursuing a doctorate from the George Washington University. His work at GSFC concentrates on instrument development applied to remote sensing technology. He recently received a Group Achievement Award and an Outstanding Achievement Peer Award on the MIR.

ROBOTICS**ROBOTIC SERVICING OF FREE-FLYING SPACECRAFT**

SATELLITE LIFE can be dramatically extended by on-orbit servicing, as demonstrated several times by astronauts on Space Shuttle missions. Other work has shown that robotic servicing through remote teleoperation, autonomous operation, or a combination thereof, can significantly reduce the time and hazards involved in these activities. Furthermore, using robotic techniques allows remote servicing of satellites out of the range of the Space Shuttle, such as those in polar or geosynchronous orbits.

The GSFC Robotics Branch has embarked on a technology development program that will provide the capabilities necessary to perform remote robotic servicing. GSFC's approach, called Contact-Proximity Guidance and Control, replaces traditional active/passive compliance methods with simple, robust, capacitance-based sensors, unique control algorithms, and three-dimensional, real-time imaging. It has been successfully demonstrated both in the GSFC Robotics Laboratory, and remotely from JPL in Pasadena, California, in which a mockup of a subsystem module was changed out from a mockup of the Explorer Platform (EP).

The technique of Contact-Proximity Guidance and Control stems directly from the use of a capacitance-based, proximity sensor, called the *capaciflector* (see GSFC R&T Reports for 1991 and 1992). Capaciflector response increases hyperbolically as the range decreases up to the point of contact. Capaciflectors can be made of any conductive material, and can assume any size and shape, such as may be used for fasteners and guiding mechanisms. The sensors require minimal software and hardware, and have been successfully tested for the space environment. The electronics utilize basic analog and digital components, with long heritages in space flight.

Capaciflectors are used in conjunction with unique control algorithms to provide alignment and collision avoidance. The contact point can be located by scanning the local area and searching for a local minimum response. This allows the robot or operator to hold the end effector at a fixed distance from an object, and "feel" its way to the contact point utilizing some *a priori* knowledge from a limited-world model. At the contact point, impact forces will be negligible due to application of a "virtual force" algorithm that reduces velocity with decreasing range. After contact, an impedance control algorithm can hold

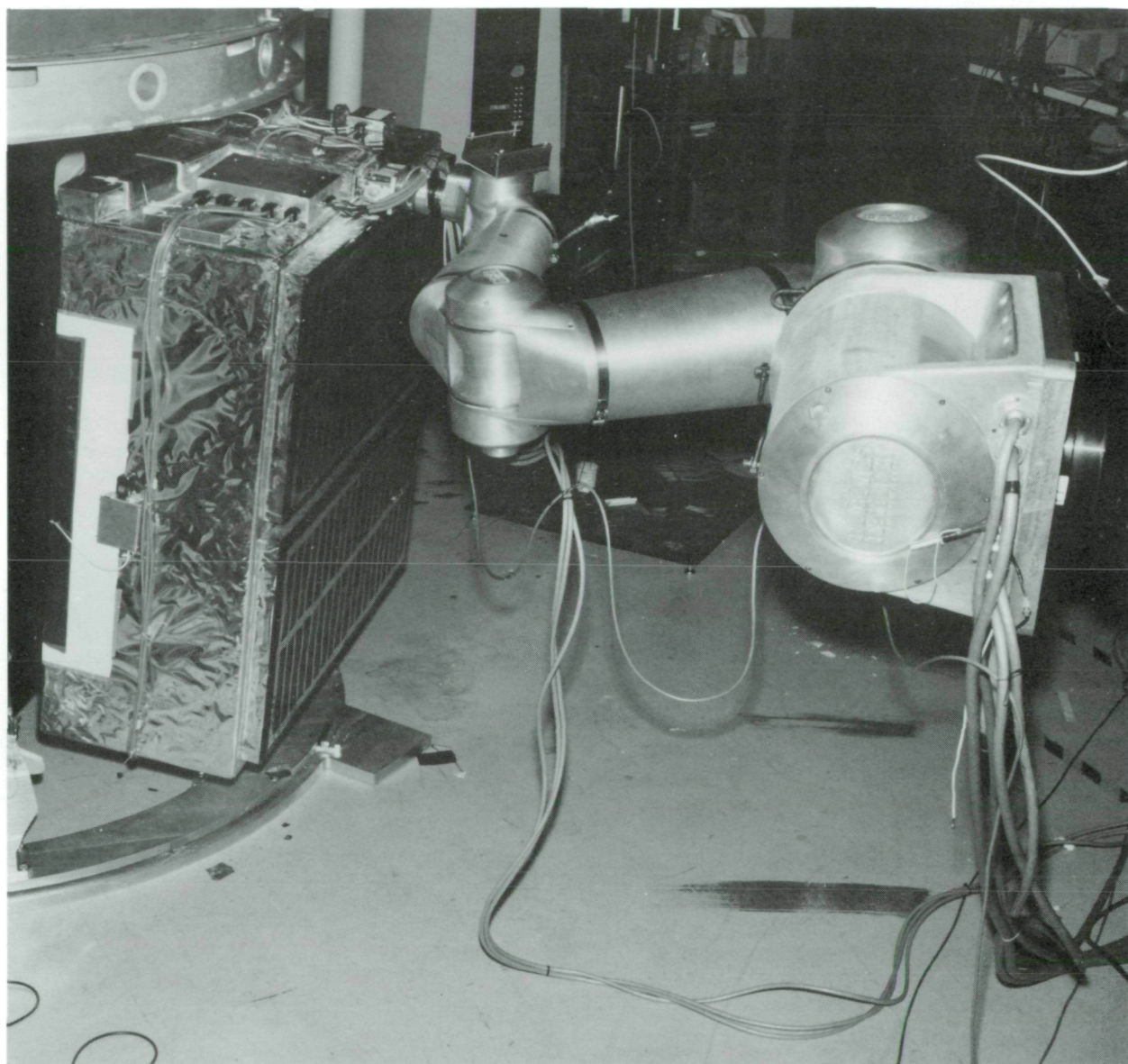
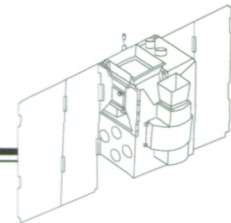
the force to a predetermined value to facilitate berthing. Simultaneous three-dimensional, real-time, capaciflector imaging is possible, providing the operator with precise alignment information up to the point of contact, unlike video-based systems that become obscured when operating space becomes limited.

As a demonstration of this technology, the GSFC EP Demonstration Project developed, integrated, and tested the changeout of a Multi-Mission Spacecraft (MMS) module using capaciflector technology and robotic controls (see the figure). The spacecraft interfaces were not altered because the spacecraft was not designed with on-board capaciflectors. The EP MMS changeout demonstration was performed in three modes: teleoperation, autonomous, and shared control. The demonstration also was performed using teleoperation remotely from JPL.

The teleoperations portion of the demonstration consisted of berthing the MMS on the EP mockup. A camera was mounted to the wrist of the robot arm to provide video images and recording. A Lightweight Servicing Tool (LST), mounted to the end of a robot arm, was mated with the MMS using a combination of the cameras and force torque sensors. The MMS was then lifted and berthed to the EP structure, and the LST was used to tighten the screws to hold the module in place.

In the autonomous control mode, the LST was fitted with a "hammerhead" capaciflector bracket. The LST was mated to the MMS module using the capaciflector range data and a search strategy based on a rudimentary world model. The LST positioned the MMS using capaciflectors placed on the sides, top, and front of the module. These capaciflectors were mounted on the replacement module only, as they were not needed for MMS extraction. This method allowed the robot to track the EP if it moved. The imaging techniques were used to locate the screw over the receptacle on the EP mockup. Virtual force control slowed the insertion to ensure minimum impact, and impedance control completed the process.

In the shared control mode, the operator moved the LST close to MMS front surface via a hand controller. Using a combination of force feedback, video images, and autonomous collision avoidance, the LST mated, lifted, and aligned the MMS with the EP mockup. Force feedback



Robot arm preparing to berth MMS Module with capaciflectors to EP mockup.

control was then used to berth the MMS to the EP. The impedance control algorithms controlled the system to provide constant force for berthing. This test was also successfully conducted from a JPL workstation in California via satellite link, demonstrating the remote teleoperation capability. JPL used advanced graphics simulations and visual displays to command the GSFC robot with a time delay of several seconds. The operator calibrated and verified the robot task via intermittent updates from a real-time video and data link.

A clear extension of the EP Demonstration Program is to apply robotic servicing to the HST project. This application utilizes contact-proximity guidance and control in shared control mode. An astronaut in the Shuttle aft flight deck (or from the ground) controls the Servicing Aid Tool (SAT) robotic arm to reduce the requirement for astronaut extravehicular activity (EVA) and intravehicular activity (IVA) by using these robotic techniques to unlatch and open the HST tool box and Small ORU Protective Enclosure (SOPE) box.

A demonstration of the tool-box opening capability has been successfully performed at GSFC. A robot arm was fitted with a three-finger gripper, each finger fitted with integrated capaciflectors. The gripper was moved to within a few inches of the tool box, at which point autonomous controls took over. Using a rudimentary world model, the gripper was first aligned with the pip pin/latch that holds the doors closed, and then grasped and pulled the pin using two fingers while the third depressed a release button. The latch was then released when a single finger pulled upward. After all pins and latches were activated, the doors were swung open and tools could be accessed.

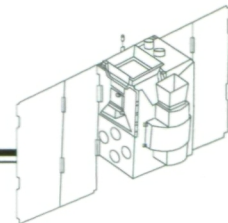
To open the SOPE box, a motorized socket-type end effector fitted with capaciflectors was aligned precisely over the J-hooks that hold the door in place. The end effector was first aligned over the J-hooks using the capaciflector information, and then torqued the release nuts, freeing the lid. A parallel jaw gripper was then used to autonomously open the SOPE box lid and exchange the Engineering Science Tape Recorder (ESTR).

Contact-proximity guidance and control has been shown to be a viable method of robotic servicing in a microgravity environment. Using advanced capaciflector proximity sensors, virtual force, and impedance control, robotic servicing can be performed in teleoperation, autonomous operation, or shared control with minimal force generation. We anticipate that these technologies will be transported to the SAT robotic system and result in more efficient and safe operation during the HST mission.

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Sponsor: Office of Advanced Concepts and Technology

Mr. Stanford Ollendorf is Head of the Robotics Branch and is responsible for the establishment of the robotics program at NASA GSFC. He has 29 years of experience in designing and implementing flight experiments on spacecraft and the Space Shuttle.



A NOVEL CLASS OF 6-DEGREE-OF-FREEDOM PARALLEL MINIMANIPULATORS

RESEARCH HAS ALREADY SHOWN that parallel manipulators provide better accuracy, rigidity, load-to-weight ratio, and load distribution than serial manipulators. However, due to the existence of loops in their architecture, parallel manipulators do not allow the large workspaces that serial manipulators do. Hybrid (serial/parallel) systems can provide both the accuracy of parallel mechanisms and the large workspace of serial manipulators. The serial portion provides the gross motion, while the parallel portion can be used for error compensation and delicate position and force control. We recently undertook an investigation of a novel class of 6-degree-of-freedom (DOF) parallel minimanipulators. The term *minimanipulator* is used because the mechanisms are not designed for providing large platform (output link) displacements, but rather are designed to provide high resolution and stiffness for fine manipulation in a hybrid system. The actuators are base-mounted. Two-DOF planar linkages and inextensible limbs are used to improve positional resolution and stiffness.

Many of the 6-DOF parallel mechanisms described in the relevant literature contain six limbs. Reducing the number of limbs in a parallel mechanism lowers the number of loops in its structure. As a result, direct kinematics of the mechanism is simplified, whereas the inverse kinematics becomes more challenging. (By *direct kinematics*, we look to determine the position of the centroid and the orientation of the platform, given actuator displacement. By *inverse kinematics*, we seek to determine the actuator displacement, given the position of the centroid and the orientation of the platform). Because direct kinematics of a parallel manipulator is much more difficult than its inverse kinematics, the minimanipulators are designed to employ a minimum number of limbs. This has additional benefits, namely, a lower number of links and joints, lower minimanipulator weight, and higher dexterity. Because three noncollinear points on a platform of a 6-DOF parallel manipulator completely define its location (position and orientation) in space, each minimanipulator contains three inextensible limbs that connect three noncollinear points on its platform to its base. Again, the limbs are designed to be inextensible to increase the stiffness and resolution of the minimanipulators.

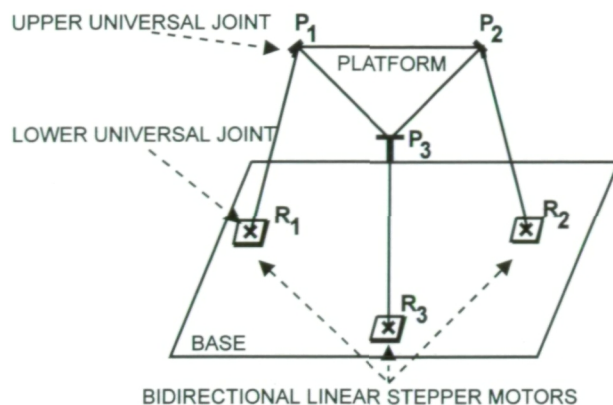
In a manipulator with base-mounted actuators, the weight of an actuator is not a load for the other actuators. As a result, higher payload capacity, smaller actuator sizes, and

lower power dissipation can be realized. Therefore, the minimanipulators are designed to have base-mounted actuators. In addition, they are symmetric (i.e., there exist identical joints and links in each limb connecting its base to its platform). The latter property is needed for even load distribution. The lower end of each limb is connected to a 2-DOF driver (e.g., a bidirectional linear stepper motor, a pantograph, or a five-bar linkage) and can be moved freely on the base plate. The desired minimanipulator motion is obtained by moving the lower ends of its three limbs on its base plate.

It has been shown that each limb of a symmetric 6-DOF parallel manipulator must have 6 DOF in its joints. Therefore, in addition to the 2-DOF provided by a driver, each limb should be given 4 additional DOF. To keep the limbs inextensible, joints are placed only at their lower and upper ends. A 3-DOF spherical joint at one end and a revolute joint at the other end can be used. However, due to difficulties in their fabrication, spherical joints are not precise and, therefore, are not used in construction of the minimanipulators. Instead, a 2-DOF universal joint is placed at each end of a limb. One of the axes of the upper universal joint is collinear with the limb, and the other axis of the upper universal joint and one of the axes of the lower universal joint are always perpendicular to the limb. This arrangement is kinematically equivalent to a limb with a spherical joint at its lower end and a revolute joint at its upper end. By using such a limb configuration, the kinematics of a minimanipulator is made independent of the output link orientation of its 2-DOF drivers.

The first figure shows a minimanipulator driven by 3 bidirectional linear stepper motors. Note that bidirectional linear stepper motors act as X-Y positioning tables, but their stators are base-mounted. To keep the minimanipulator geometrically symmetric, axes of the topmost revolute joints at points P_1 , P_2 , and P_3 are made parallel to lines P_2P_3 , P_1P_3 , and P_1P_2 , respectively.

Two-DOF planar pantographs and five-bar linkages can also be used as drivers. Such mechanisms are capable of increasing the mechanical advantage of the minimanipulators; as a result, better positional resolution and stiffness can be obtained. The second figure shows a five-bar linkage driver. Base-mounted rotary actuators are placed at points D and E . It has been shown that the smaller

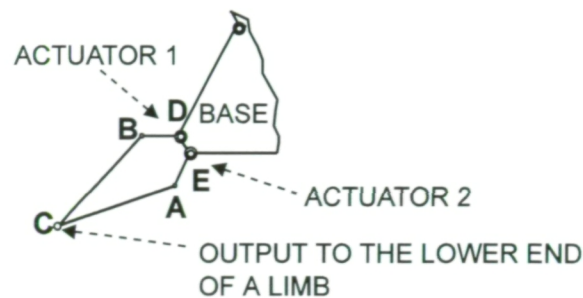


A typical minimanipulator.

the input link lengths (EA and DB) with respect to the other link lengths (AC and BC), the higher the stiffness of the driver. Hence, the input links of the five-bar linkage driver are made much smaller than its output links.

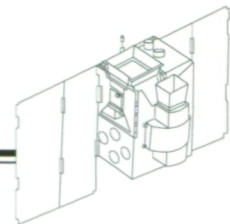
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Sponsor: GSFC Research and Study Fellowship Program



Five-bar linkages and 2-DOF drivers.

Dr. Tahmasebi is assigned to the Applied Robotics Research Section. He graduated Summa Cum Laude with a BS and a PhD in Mechanical Engineering from the University of Maryland. He has been at GSFC since 1983, and received a patent for the Six-Degree-of-Freedom Parallel Minimanipulators. He has also taught graduate and undergraduate-level courses in Mechanical Engineering at the University of Maryland, College Park.



TRIP-ROLLER CLUTCH

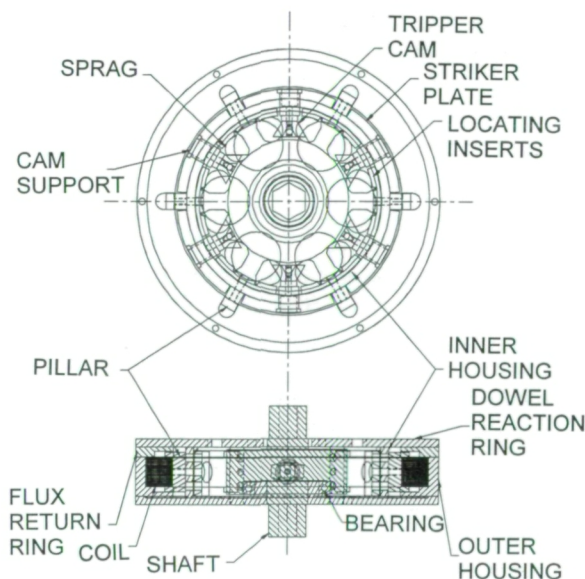
ELECTROMAGNETIC BRAKES depending on friction holds are commonly used as brakes for electric motors and drives. These are normally weak and so are configured such that a transmission speed reducer is used to increase their apparent performance. This creates design penalties in the electromechanical joint, and, even with the help of a transmission, such brakes are often too heavy, too large, and require too much power. With the hysteresis/friction encountered by requiring back-torques to go through the gear train as well as the brake, and because of the large inductance in the transmission oil, these systems cannot perform efficiently as a precision slip (safety) clutch. To improve performance, toothed brakes have been employed. These, however, have problems of their own. Since they have teeth, they position digitally, and thus they do not give continuous, analog, precision positioning. They also have difficulties releasing under load. They tend to make hard tooth-to-tooth contact under large loads and develop extreme frictional forces between the teeth. Also, in an effort to minimize magnetic solenoid size and weight, the teeth are made short. This invites the teeth to jump over each other during the extreme vibrations such as are encountered during spacecraft launch.

A third, though less common, technique involves magnetic particle clutches/brakes. These use a magnetic field to align magnetic particles in a gap between rotating members, and thus create frictional forces which bind the two members together. The magnetic particles are steel or iron in a powder form; in some variants they can also be suspended in liquid. In general, these systems tend to wear out by grinding the particles down until they lose their friction-holding capability. As a result, they are not totally reliable. The liquid variants must remain absolutely sealed to prevent leakage and outgassing. These have, for the most part, been abandoned for common usage.

The concept of the Trip-Roller Clutch was developed to provide a high-performance combination brake/slip clutch that will overcome some of the weaknesses described above, and will improve the performance of associated electromagnetic systems in a fundamental sense. A novel, adaptive, computer-controlled mechano-electronic device, this system will excel both as a brake and as a precision slip clutch. Its high performance potential derives from: (1) the exceptional strength and stiffness in an exception-

ally compact package, which results from roller locking; (2) continuous analog positioning; (3) positive, reliable release under load using minimal power due to a novel, simple, tripping technique; (4) precision, high-fidelity slipping on command, due to the inherent high efficiency of the roller-based system; and (5) unprecedented safety, due to both its large holding strength and its ability to release under large loads, with thresholds that can change in real-time in response to sensors and computer control in a closed-loop configuration.

The Trip-Roller Clutch prototype, diagrammed in the figure, illustrates the essential ingredients of the operational concept. It uses six sets of roller-locking cams (or sprags) organized in pairs. One half of each pair opposes rotation in the clockwise direction; the other half opposes rotation in the counterclockwise direction. Because roller locking is used, this brake is very strong. The harder it is turned, the harder it holds, until contact stresses are exceeded. The technical challenge is to get the system to release under load.



Six sets of sprags organized in pairs give the trip-roller clutch bidirectional braking. Release under load is accomplished by tripper cams that force the sprags to slip until a magnetic solenoid "pops" the sprags and the system free-wheels.

ENGINEERING AND MATERIALS

Comparison of Electromagnetic Brake/Clutch Torques and Volumes.

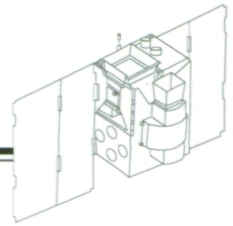
Company	Model	Type/Description	Max. Torque	Gross Dimensions Shaft Excluded (in)	Volume	Power (W)
Dynamic Group	2-62010-24	Unipac brakes, spring set and EM disc brakes	10 ft-lbs	6.875 diam x 4.25	157.770	unavailable
	2-63015-24		15 ft-lbs			unavailable
	2-63020-24		20 ft-lbs			unavailable
Electroid	series 36	EM friction clutch	7.92 ft-lbs	3 diam x 3	21.206	8.1
	series 42		20 ft-lbs	4.25 diam x 3	42.559	11.7
Magnetic Particle Devices	EPB-120	clutch	10 ft-lbs	5.45 diam x 4.015	93.663	unavailable
	EPB-120-125	brake	10 ft-lbs	5.45 diam x 2.19	51.089	unavailable
	EPC/B	brake/clutch module	10 ft-lbs	5.45 diam x 5.25	122.474	unavailable
Warner	EP 250	Electric clutches and brakes	10 ft-lbs	8.969 x 4.25 x 5.281	127.233	7.5
	EP 400		23 ft-lbs	11.781 x 6 x 6.938	333.110	7.9
Honeybee Robotics		EM brake/clutch	20 ft-lbs	4.625 diam x 1	18.665	6.0

To release under load, the magnetic solenoid is actuated, which attracts each striker plate radially outward (there is one striker plate for each set of clockwise-counterclockwise sprags). Attached to each striker plate is a 2-way tripper cam; this tripper cam, in turn, slides in two slots in the grounded housing. Thus, when a striker plate moves radially outward, it continues until its tripper cam encounters a pair of locking sprags, at which point it stops. If we assume clockwise braking, the striker plate will make the counter-clockwise sprag move out of the way, but will be stopped by the clockwise sprag. It will then seat against both the clockwise sprag and the slots in the device housing. This will happen for all six striker plates/tripper cams, each of which independently will be attracted radially towards the solenoid, and each of which independently will seat against its respective clockwise sprags and the device housing.

For a roller-locking system to maintain load, it must roll microscopically. Each striker/tripper has the effect of inhibiting and blocking that forward rolling motion. As a result, each sprag begins to slip, changing its coefficient of friction from static to the less formidable dynamic value. This makes it easier for the solenoid to prevail and so it is able to "pop" the clockwise sprags out and allow the system to free-wheel. Very little power is required because the springs holding the strikers in place are, by design, very weak. The brake depends on these springs for positioning only; they are not central to its holding strength. Once the strikers free their respective locking sprags, they

each will contact the wall of the solenoid, complete the magnetic circuit, and permit the power to drop to a minimal level. When the solenoid is de-energized, the spring of each striker plate disengages that striker plate/tripper cam from its respective roller locking sprags, the sprag positioning springs cause the sprags to engage, and the system is locked. It is thus locked fail-safe when the power is off. Each sprag has a gear which locates it with respect to the device housing. This gear is constructed so as not to interfere with the roller-locking operation of its sprag.

We constructed and tested a prototype of this assembly. The trip roller clutch prototype is relatively crude and oversized, designed primarily to prove concept and oversized to permit easy access to parts for tweaking and observation purposes. Unhardened components were used at the stress points and no optimization was attempted in this test device. Also, no attempts were made to minimize electrical power consumption. This prototype merely tested the mechanical aspects of the concept. The prototype measured 4.625-in diameter x 1-in axial length. It had a volume of 18.665 in³ and weighed about 5 lbs. It produced 20 ft-lbs holding torque and used about 60 watts of power. It was able to release under load. The table shows that this prototype compares very favorably with commercially available brakes and clutches. Clearly, this is a superior concept for a brake clutch which will, undoubtedly, find its way into the NASA repertoire of devices used in space. However, the device did not "free-wheel" when it released under extreme loading, but rather retained



residual frictional drag. There appears to be a solution for this problem; it will be tested as the trip- roller clutch continues to be developed.

The trip roller clutch seems destined for NASA space applications in all manners of electromechanical joints, from robotics to basic deployment mechanisms. Furthermore, this device will, inevitably, have many applications in industry, ranging from drives, clutches, and transmissions in electric vehicles, to basic materials and people-moving devices.

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ACRONYMS

A/D	analog-to-digital	CDMA	Code Division Multiple Access
ABA	Aberrated Beam Analyzer	CDS	correlated double sampling
ACE	Advanced Composition Explorer	CGH	Computer-Generated Hologram
ADC	analog-to-digital conversion	CGRO	Compton Gamma Ray Observatory
ADS	Angular Displacement Sensor	CID	charge-injection device
AFM	articulating-fold mirrors	CMBR	Cosmic Microwave Background Radiation
AGI	Analytical Graphics, Inc.	CMS	Command Management System
AGNS	Automated Ground Network System	COBE	Cosmic Background Explorer
AOCS	Attitude and Orbit Control System	COSTAR	Corrective Optics Space Telescope Axial Replacement
AP	Application Processor	COTS	commercial off-the-shelf
ASCA	Advanced Satellite for Cosmology and Astrophysics	CRC	cyclic redundancy check
ASIC	Application-Specific Integrated Circuit	CRPE	French National Center for Telecommunications
ASTRO-D	Spectroscopic X-ray Observatory	CW	continuous wave
AVHRR	Advanced Very High Resolution Radiometer	CXB	Cosmic X-ray Background
		CZCS	Coastal Zone Color Scanner
BATSE	Burst and Transient Source Experiment	DA	Demand access
BBXRT	Broadband X-ray Telescope	DAAC	Distributed Active Archive Center
BOL	Beginning of Life	DADS	Data Archive and Distribution System
BOREAS	Boreal-Ecosystem Atmosphere Study	DAMT	Distributed Applications Monitor Tool
BPSK	binary phase-shift keyed	DC	direct current
		DCI	Distributed Computing Initiative
CAS	COSTAR Alignment System	DDF	Data Distribution Facility
CCD	charge-coupled device	DF	development facility
CCSDS	Consultative Committee for Space Data Systems	DIAL	Differential Absorption Lidar

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ACRONYMS

DIRA	Digital Integrating Rate Assembly	FAS	Facilities Automation System
DIRBE	Diffuse Infrared Background Experiment	FAST	Fast Auroral Snapshot Explorer
DMR	Differential Microwave Radiometer	FFT	fast Fourier transform
DOB	Deployable Optical Bench	FIFE	First ISLSCP
DPCP	Distributed Process Control Program	FIRAS	Far Infrared Absolute Spectrophotometer
DSP	Digital Signal Processing	FM	frequency modulation
DU	Dobson unit	FOC	Faint Object Camera
		FOC-STM	FOC-Structural Thermal Model
e-p	evaporation minus precipitation	FOS	Faint Object Spectrograph
ECAS	Engineering Change Automation System	FSE	File Server Elements
ECS	EOS Core System	FSM	First Servicing Mission
EDLC	Evolutionary Domain Life Cycle	ftp	file transfer protocol
EGRET	Energetic Gamma Ray Experiment Telescope	FUSE	Far Ultraviolet Spectroscopic Explorer
ELIMS	Enhanced Logistics Information Management System	FUV	far ultraviolet
EO	electro-optic		
EOF	Experimenter Operations Facility	GAMES	Gravity and Magnetic Earth Surveyor
EOL	End of Life	GCM	Global Circulation Model
EOS	Earth Observing System	GDAAC	Goddard Distributed Active Archive Center
EOSDIS	EOS Data and Information System	GenSAA	Generic Spacecraft Analyst Assistant
ERBE	Earth Radiation Budget Experiment	GEOS	Goddard Earth Observing System
ESA	European Space Agency	GGAO	Goddard Geophysical and Astronomical Observatory
ESDIS	Earth Science Data and Information System	GHRS	Goddard High Resolution Spectrograph
EVA	extra-vehicular activity	GN	Ground Network

ACRONYMS

GOES	Geostationary Operational Environmental Satellite	IRAS	Infrared Astronomy Satellite
GOSIP	Government Open Systems Interconnection Profile	IRIS	Infrared Interferometer Spectrometer
GOTT	Ground Operations Technology Testbed	ISAS	Institute of Space and Astronautical Science (Japan)
GRO	Gamma Ray Observatory	ISCCP	International Satellite Cloud Climatology Project
GRTS	GRO Remote Terminal System	ISEE	International Sun-Earth Explorer
GSFC	Goddard Space Flight Center	ISLSCP	International Satellite Land Surface Climatology Project
GSMS	Graphical Spacecraft Monitoring System	ISO/OSI	International Standards Organization/ Open Systems Interconnection
GTE/TRACE-A	Global Tropospheric Experiment/ Transport and Atmospheric Chemistry near the Equator-Atlantic	ISTP	International Solar Terrestrial Physics
GUI	Graphical User Interface	ITCZ	Inter-Tropical Convergence Zone
		IUE	International Ultraviolet Explorer
HEAO	High Energy Astrophysics Observatory	IUESIPS	IUE Spectral Image Processing Image
HPA	High Power Amplifiers	IVT	Independent Verification Team
HRI	High Resolution Imager	IWS	instrument workstation
HSP	High Speed Photometer		
HST	Hubble Space Telescope	JPL	Jet Propulsion Laboratory
HTS	high-temperature superconductor		
		kbps	kilobit per second
IF	intermediate frequency	KBSEE	Knowledge-Based Software Engineering Environment
IMC	Image Motion Compensation	kpc	kiloparsec
IMS	Information Management System	KSC	Kennedy Space Center
INR	Image Navigation and Registration		
IPD	Information Processing Division	LAD	Liquid Acquisition Device
IPM	interplanetary medium	LAN	local-area network
		LASCO	Light and Spectrometric Coronagraph

ACRONYMS

LASP	Laboratory for Astronomy and Solar Physics	NCC	Network Control Center
LED	light-emitting diode	NEWSIPS	New Spectral Image Processing System
LES	large eddy simulations	NICMOS	Near-Infrared Camera and Multi-Object Spectrometer
LHEA	Laboratory for High Energy Astrophysics	nm	nanometer
lidar	light detection and ranging	NMC	National Meteorological Center
LLJ	low-level jet	NOAA	National Oceanic and Atmospheric Administration
LPNMS	Large Probe Neutral Mass Spectrometer	NRT	near-real-time
LRI	Laser Ranging Instrument	NSSDC	National Space Science Data Center
LTE	local thermal equilibrium	OIMS	Orbiter Ion Mass Spectrometer
LWP	long wavelength primary	OLR	outgoing longwave radiation
MA	multiple access	OTA	Optical Telescope Assembly
Mb	megabytes		
MCS	Monitor and Control Subsystem	p-r	photoionization-recombination
MESFET	metal semiconductor field-effect transistor	PATS	Pointing, Acquisition, and Tracking Subsystem
MGE	Media Generation Elements	PBL	planetary boundary layer
MIMD	multiple-instruction/multiple data	pc	parsec
MIPS	million instructions per second	PCS	Predefined Command Sequences
MIT	Massachusetts Institute of Technology	PDB	Project Database
MMC	Mirror Motion Compensation	PFF	Pluto Fast Flyby
MOC	Mission Operations Center	PGS	Product Generation System
MSAM	Medium Scale Anisotropy Measurement	PI	Principal Investigator
MSE	Mission Service Element	pin	p-type/intrinsic
MSN	Maintenance and Support Network	PMG	Plasma Motor Generator
NASA	National Aeronautics and Space Administration	PN	pseudorandom noise
		POCC	Payload Operations Control Center

ACRONYMS

POMM	Pickoff Mirror Mechanism	SeaWiFS	Sea-viewing Wide Field-of-View Sensor
PORTS	Project Operations Real-Time System	SEDS	Small Expendable Deployer System
PPF	photosynthetic photon flux	SERTS	Solar Extreme Ultraviolet Telescope and Spectrograph
ppm	parts per million	SFDU	Standard Formatted Data Unit
PRS	POCC Refurbishment System	SHOOT	Superfluid Helium On-Orbit Transfer
PSK	phase-shift keyed	SIMD	single-instruction/multiple data
PSPC	Position-Sensitive Proportional Camera	SIPE	Scientific Instrument Protective Enclosure
PVO	Pioneer Venus Orbiter	SME	*System Management Element
		SMEX	Small Explorer
RAS/HOMS	Refractive Aberrated Simulator/ Hubble Opto-Mechanical Simulator	SMM	Solar Maximum Mission
RCR	Remote Command Request	SMMR	Scanning Multichannel Microwave Radiometer
rf	radio-frequency	SMOC	SOHO MOC
rms	root mean square	SN	Space Network
RMT	Rapidly Moving Telescope	SOFDS	Synchronous Output Flight Data System
ROSAT	Röntgen Satellite	SOHO	Solar and Heliospheric Observatory
ROSE	Request-Oriented Scheduling Engine	SQL	Structured Query Language
RPR	Remote Procedure Request	SRM	Satellite-Raingauge Model
		SSA	S-band Single Access
SAFARI	Southern African Fire Atmospheric Regional Initiative	SSC	Satellite Situation Center
SAMPEX	Solar, Anomalous, and Magneto-spheric Particle Explorer	SSM/I	Special Sensor Microwave/Imager
SAR	Synthetic Aperture Radar	SSPA	Solid-State Power Amplifier
Satcom	Satellite communications	SST	sea-surface temperature
SBUV	Solar Backscatter Ultraviolet	STDN	Spaceflight Tracking and Data Network
SCR	Strip Chart Recorder	STIS	Space Telescope Imaging Spec-trograph

ACRONYMS

STK Satellite Tool Kit

SXT Soft X-ray Telescope

TAC Telemetry and Command

TASS TPOCC Advanced Spacecraft Simulator

TDRS Tracking and Data Relay Satellite

TDRSS Tracking and Data Relay Satellite System

THIR Temperature-Humidity Infrared Radiometer

TIP Technical Information Program

TOA top of the atmosphere

TOGA/COARE Tropical Ocean Global Atmosphere/ Coupled Ocean Atmosphere Response Experiment

TOMS Total Ozone Mapping Spectrometer

TPCE Telemetry Processing Control Environment

TPOCC Transportable Project Operations Control Center

TRMM Tropical Rainfall Measuring Mission

TSDIS TRMM Science Data and Information System

TTL transistor-transistor logic

TURFTS TDRSS User RF Test Set

TWTA Travel Wave Tube Amplifiers

UARS Upper Atmosphere Research Satellite

UIL User Interface Language

URAP Unified Radio and Plasma Wave

UV ultraviolet

UVCS Ultraviolet Coronal Spectrometer

UWG User Working Group

VEST Vehicle Electrical System Test

VLSI very large scale integration

VME Bed VMEbus Block Error Detector

WAN Wide Area Networks

WF/PC Wide Field/Planetary Camera

WLC White Light Coronagraph

XTE X-ray Timing Explorer

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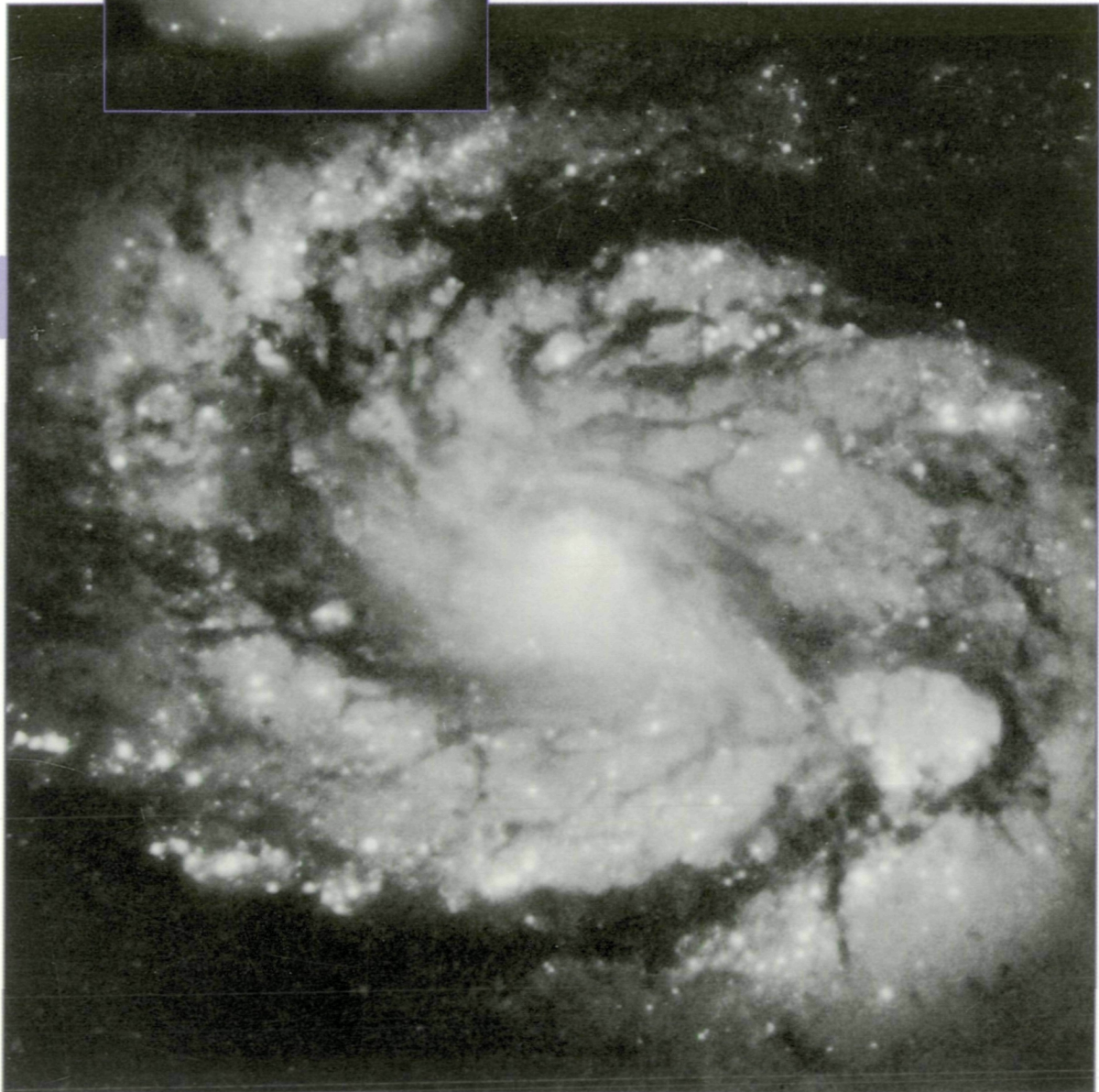
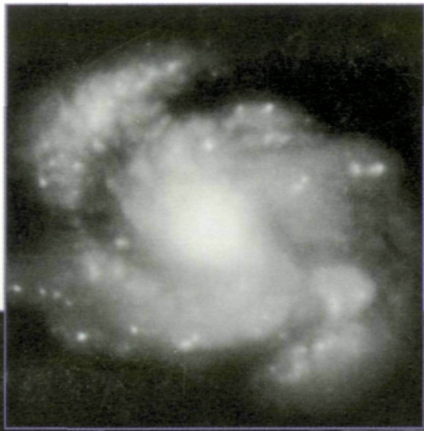
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The logos used as headers for each section of this Report are symbolic of activities addressed by each of the five major GSFC work areas. Flight Projects are represented by the Earth Observing System (EOS) AM-1 platform, currently under development for a 1998 launch to examine factors contributing to global change. Space Sciences' contributions to fundamental understanding of the Universe are represented by the Cosmic Background Explorer (COBE), built entirely in-house at GSFC. Earth Sciences are represented by the Upper Atmosphere Research Satellite (UARS), the first observatory of the Mission to Planet Earth. Mission Operations and Data Systems are represented by a Tracking and Data Relay Satellite (TDRS), the heart of the spacecraft communications network. Engineering is represented by a Small Explorer (SMEX)-class spacecraft—the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX)—symbolic of GSFC's commitment to providing high-quality scientific instrumentation and spacecraft.

Front cover: A montage of wire-frame diagrams showing Hubble Space Telescope (HST) mounted in the Space Shuttle Endeavour's cargo bay symbolizes Goddard Space Flight Center's lead role in the HST First Servicing Mission.

Back cover: Evidence of mission success came with this remarkable image of the core of the spiral galaxy M100, taken with the second-generation Wide Field and Planetary Camera (WF/PC-II) installed during the HST Servicing Mission. The dramatic improvement over a similar image taken with WF/PC-I before the Servicing Mission (inset) is easily seen. Images of this clarity and sensitivity are unprecedented in the history of astronomy.



HST/WFPC, December 31, 1993